CEPC opportunities for X,Y,Z exotica studies

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Multiquark states have been discussed since the 1st page of the quark model

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

M. Gell-Mann, Phys. Lett. 8, 214 (1964)

Where are they??

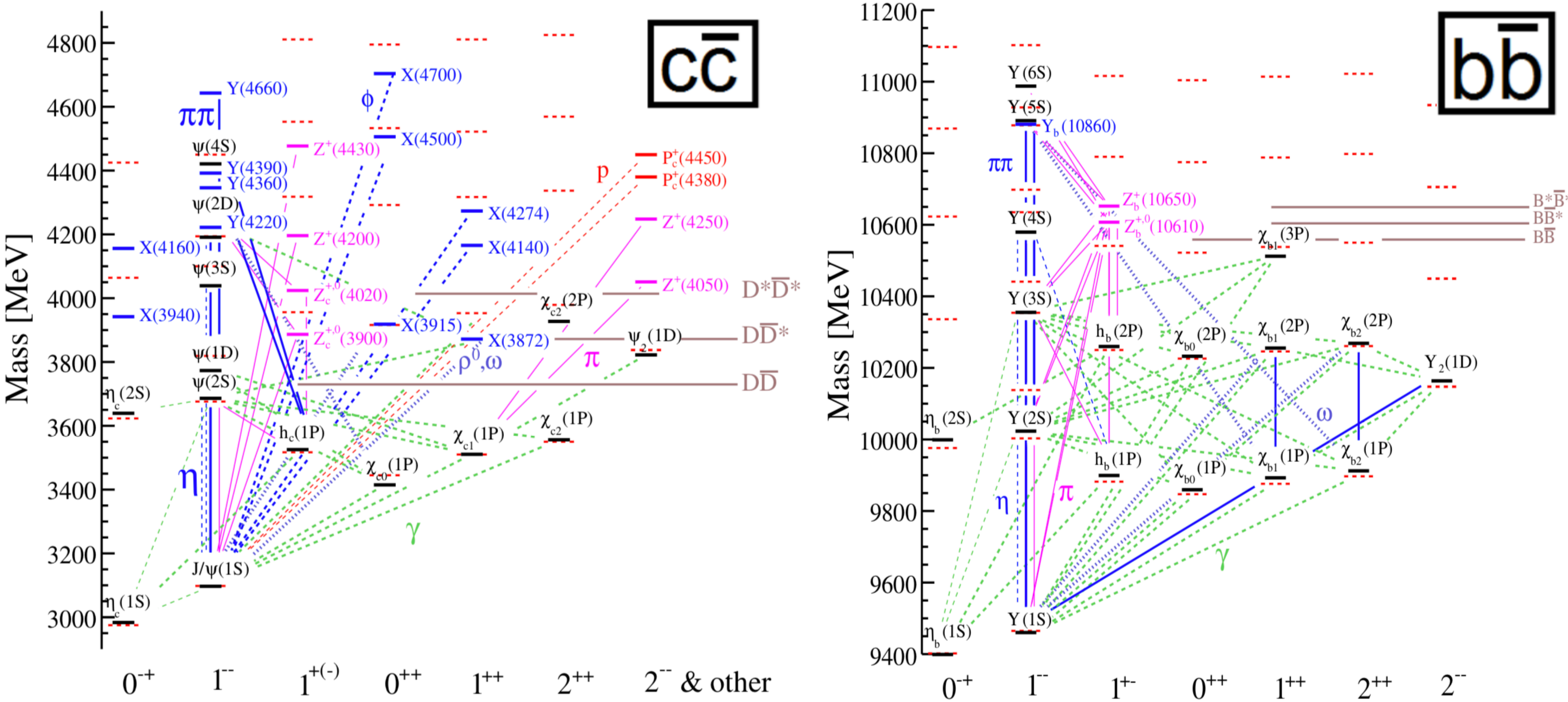
If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\bar{q})$ similarly gives just **1** and **8**.

Quarknium and Quarkonium-like exotic hadrons



Rev. Mod. Phys. 90, 015003 (2018)

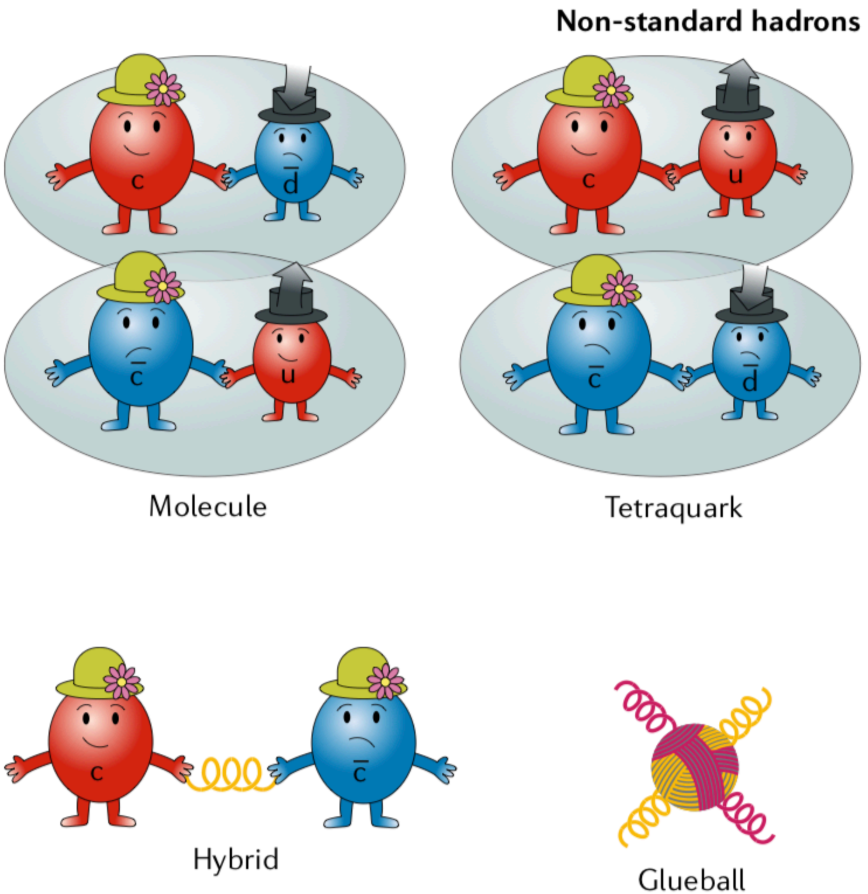
Classification:

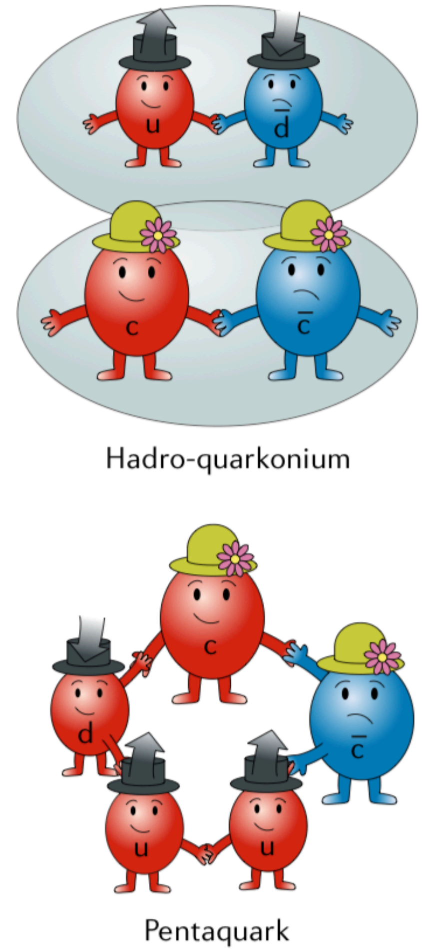
- $Q\bar{Q}q\bar{q}$
- $Q\bar{Q}qqq$: P_c^+

X: Neutral, $J^{PC} \neq 1^{--}$; Y: Neutral, $J^{PC} = 1^{--}$; Z: Charged

- Quarkonium: $q\bar{q}$, the simplest system of a hadron.
- Below $D\bar{D}/B\bar{B}$ thresholds – both charmonium and bottomonium are successful stories of QCD.
- But there are many exotic states observed in the past decade, and they are hard to fit in the two families.

Too many models !





Besides above models, there still are screened potential, cusps effect, final state interaction …

Nature Reviews Physics 1, 480 (2019)

<u>High Priority:</u>

- Identify most prominent component in wave function
- Seek unique picture describing all XYZ states, not state-by-state

Outline

- Production at different experiments
- Absolute branching fractions of the X(3872) decays
- Pentaquark states with heavy quarks
- Doubly heavy baryons in charm and beauty
- Heavy tetraquarks $QQ\bar{Q}\bar{Q}$
- Summary

Production at different experiments

Particle	Tera-Z	Belle II	LHCb
b hadrons	10^{12} Z-boson decays		50 fb^{-1}
B^+	6×10^{10}	3×10^{10} ($50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S)$)	3×10^{13}
B^0	6×10^{10}	3×10^{10} ($50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S)$)	3×10^{13}
B_s	2×10^{10}	3×10^{8} ($5\,\mathrm{ab}^{-1}$ on $\Upsilon(5S)$)	8×10^{12}
b baryons	1×10^{10}		1×10^{13}
Λ_b	1×10^{10}		1×10^{13}
c hadrons			
D^0	2×10^{11}		
D^+	6×10^{10}		
D_s^+	3×10^{10}		
Λ_c^+	2×10^{10}		
τ^+	3×10^{10}	5×10^{10} ($50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S)$)	

- Similar statistical sample of $B^{\pm}$ and B^0 at Belle II and CEPC
- Two order of magnitude more B_s at CEPC wrt Belle 2
- An abundant b-baryon sample at the CEPC

From CPC CDR Section 2.5.

The hadronization fractions from Refs. [EPJC 77, 895 (2017), EPJC 75, 19 (2015)] are applied.

Tera-Z at CEPC v.s. LHCb v.s. Belle II

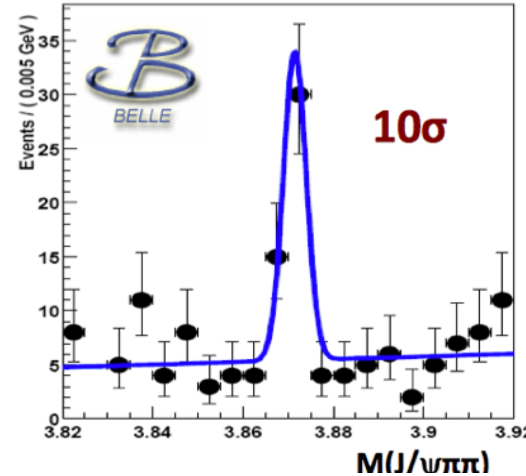
➢ **LHCb**
- **pp collisions, hadronic environment**
- **forward detector, small acceptance**

➢ **Belle II**
- **threshold production of $b\bar{b}$ resonances from e^+e^-**
- **"cleaner environment", less hadronic activities**
- **target goals $\mathcal{L}$ = 50 ab^{-1} on Υ(4S) and nearby**

➢ **Tera-Z at CEPC (production of 10^{12} Z's)**
- **no phase-space limitations like Belle II**
- **4π coverage**
- **LEP environment, less hadronic activity than LHCb**
- **allows reconstruction of final states with multiple neutrals like photons, neutral pions and kaons.**
- **decay products of Z more boosted than at Belle II**

Absolute branching fractions of the X(3872) decays

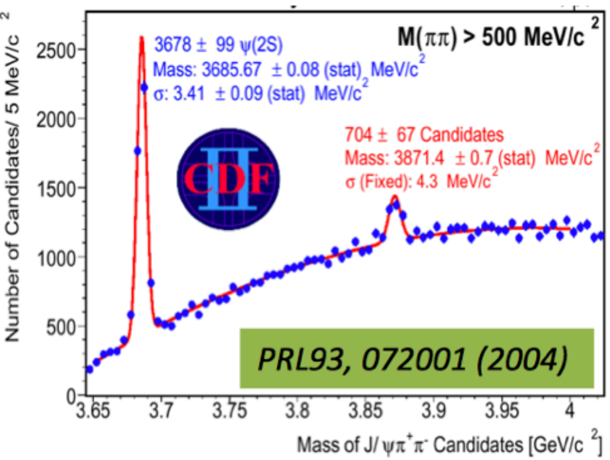
X(3872)→J/ψπ⁺π⁻

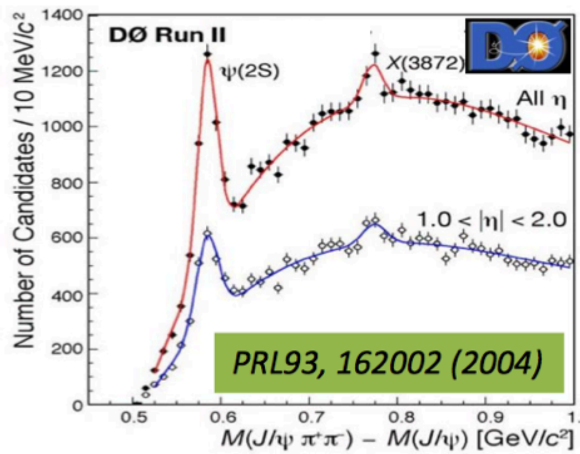


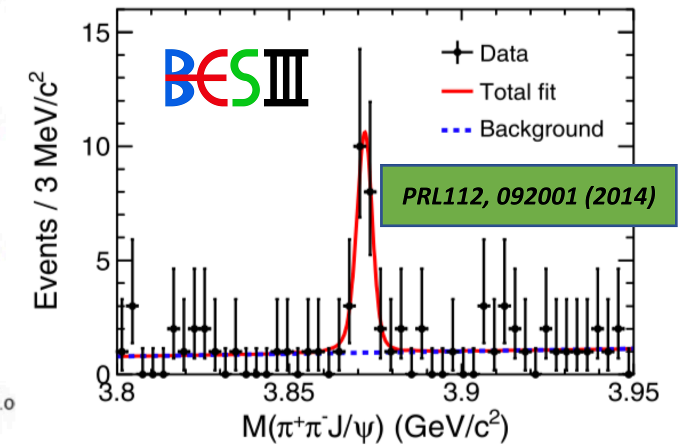
The most-cited article at Belle: 1800+

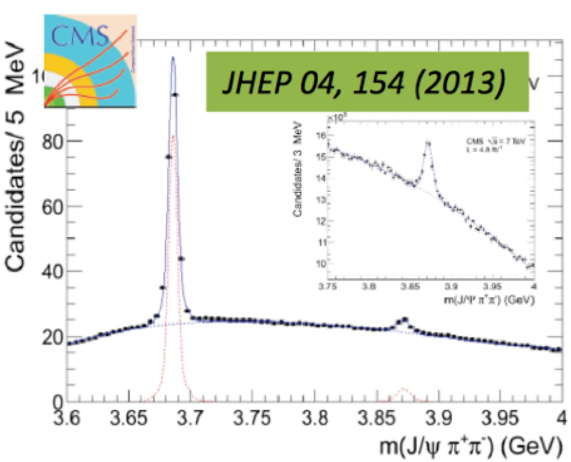
First observed by Belle in $B \to K\,J/\psi\pi^+\pi^-$ ***PRL91, 262001 (2003)***

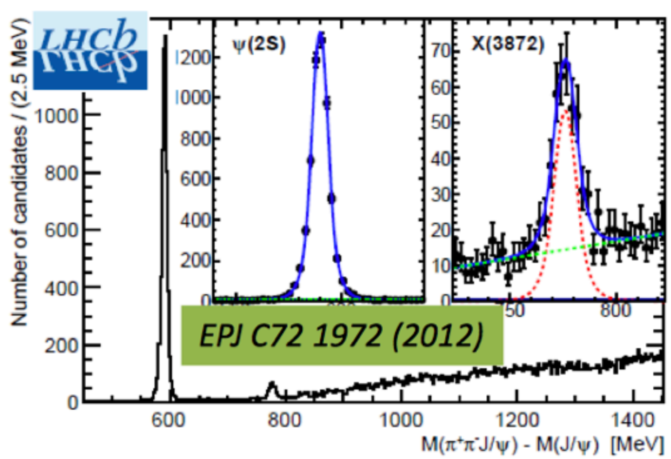
- M_X close to $D^0\bar{D}^{*0}$ threshold M = (3871.68±0.17) MeV
- Surprisingly narrow: $\Gamma_{tot} < 1.2$ MeV at 90% C.L.











X(3872)→J/ψγ: C-even

Angular analysis:

Belle 2006: $J^{PC} = 1^{++}$ or ≥2

CDF 2008: $J^{PC} = 1^{++}$ or 2^{-+}

Belle 2011: $J^{PC} = 1^{++}$ or 2^{-+}

LHCb 2013: $J^{PC} = 1^{++}$

What is X(3872)?

Decay Modes ▸ Expand all decays

Mode		Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P (MeV/c)
Γ_1	e^+e^-			1936
Γ_2	$\pi^+\pi^- J/\psi(1S)$	$> 3.2\%$		650
Γ_3	$\rho^0 J/\psi(1S)$			-1
Γ_4	$\omega J/\psi(1S)$	$> 2.3\%$		-1
Γ_5	$D^0\overline{D}^0\pi^0$	$> 40\%$		117
Γ_6	$\overline{D}^{*0}D^0$	$> 30\%$		4
Γ_7	$\gamma\gamma$			1936
Γ_8	$D^0\overline{D}^0$			520
Γ_9	D^+D^-			502
Γ_{10}	$\gamma\chi_{c1}$			344
Γ_{11}	$\gamma\chi_{c2}$			303
Γ_{12}	$\pi^0\chi_{c2}$			274
Γ_{13}	$\pi^0\chi_{c1}$	$> 2.8\%$		319
Γ_{14}	$\pi^0\chi_{c0}$			
Γ_{15}	$\gamma J/\psi$	$> 7\times10^{-3}$		697
Γ_{16}	$\gamma\psi(2S)$	$> 4\%$		181
Γ_{17}	$\pi^+\pi^-\eta_c(1S)$	not seen		745
Γ_{18}	$\pi^+\pi^-\chi_{c1}$	not seen		218
Γ_{19}	$p\overline{p}$	not seen		1693

Till now, absolute BR(X(3872)→FS) has not been established.

- **Molecular of $D^0\overline{D}^{*0}$**

Various models predict Br(X→ $J/\psi\pi^+\pi^-$) < 10% (PRD 72, 054022 (2005), PRD 69, 054008 (2004), Chin.Phys. C43 12, 124107 (2019))

- **Mixture of $D^0\overline{D}^{*0}$ and $\chi_{c1}(2P)$ bound state**

Br(X→ $J/\psi\pi^+\pi^-$) $<$ 20% (PLB 702, 359 (2011))

- **Tetraquark model**

Br(X→ $J/\psi\pi^+\pi^-$) $\sim$ 50% (PRD 71, 014028 (2005))

- **$\chi_{c1}(2P)$**

Br(X→ $\gamma J/\psi$) $\sim$ 0.6%, Br(X→ $\gamma J/\psi$) $\sim$ 3.5% (PRD 69, 054008 (2004))

Productions of X(3872)

- **B decays**: Belle, BaBar, LHCb

$B \to X(3872)K,\ X(3872) \to \text{channel}$

- **Radiative decay in e^+e^- annihilations**: BESIII

$e^+e^- \to X(3872)\gamma,\ X(3872) \to \text{channel}$

- **Λ_b^0 decays**: LHCb

$\Lambda_b^0 \to X(3872)pK^- \to J/\psi\pi^+\pi^- pK^-$

- **Prompt high energy hadron colliders**: CDF, DØ, CMS

$pp/p\bar{p} \to X(3872),\ X(3872) \to J/\psi\pi^+\pi^-$

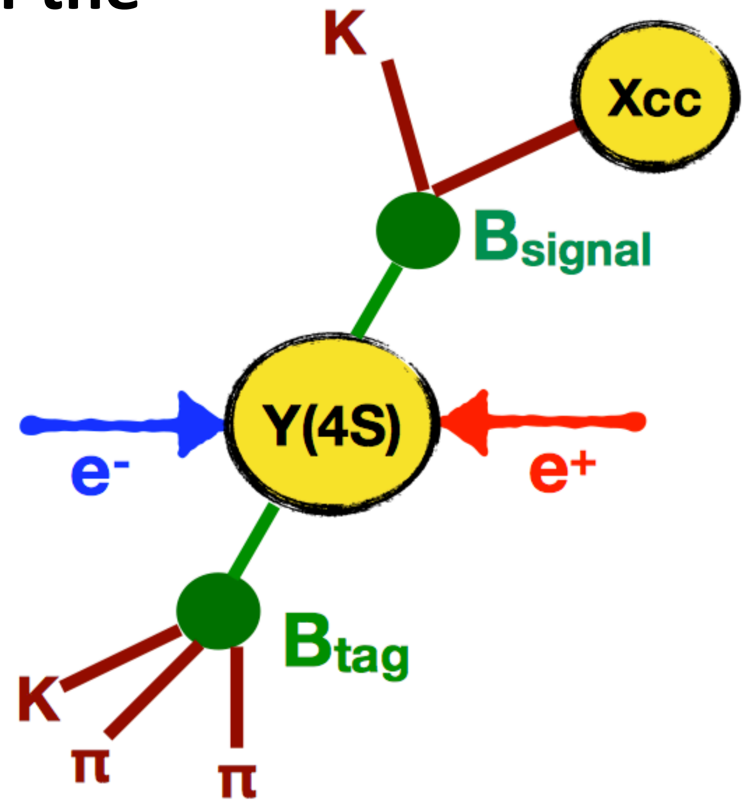
- **Photoproduction reactions**: COMPASS

$\mu^+N \to \mu^+J/\psi\pi^+\pi^-\pi^\pm N'\ (\widetilde{X}(3872))$

Belle and BaBar attempted to measure the absolute branching fractions of the X(3872) in B decays.

- B_{tag} is reconstructed in hadronic decays with high efficiency.
- The signal as a peak at the nominal X(3872) mass in the distribution of missing mass.

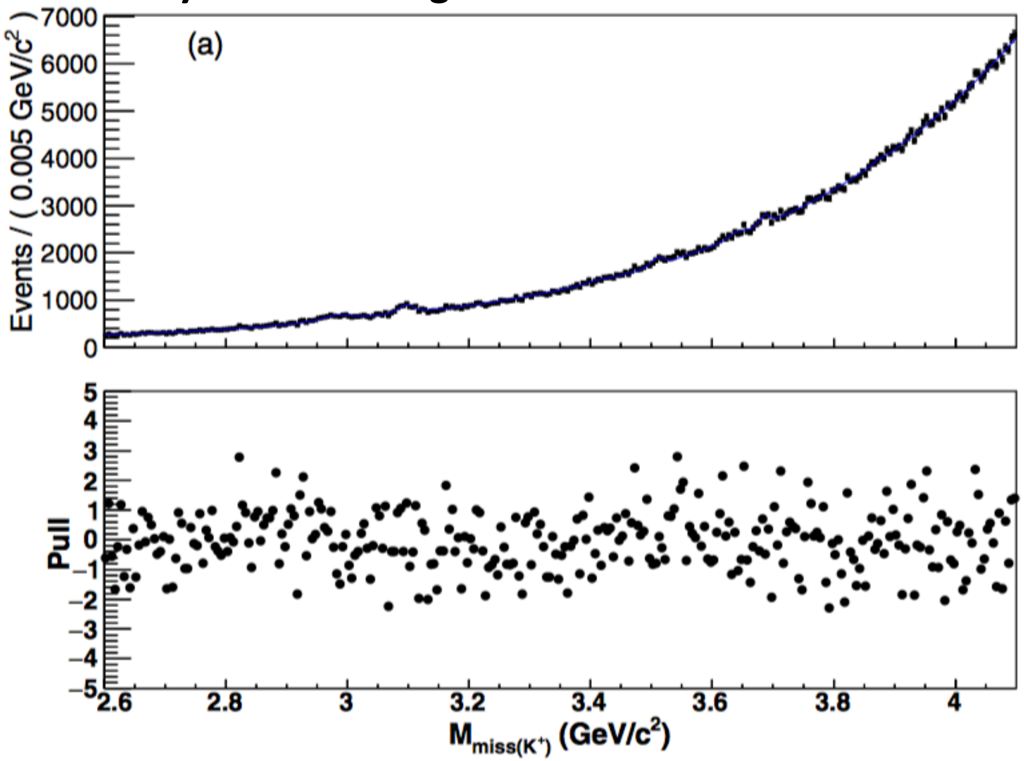
$$M_{\mathrm{miss(h)}} = \sqrt{(p^*_{\mathrm{e^+e^-}} - p^*_{\mathrm{tag}} - p^*_{\mathrm{h}})^2/c}$$

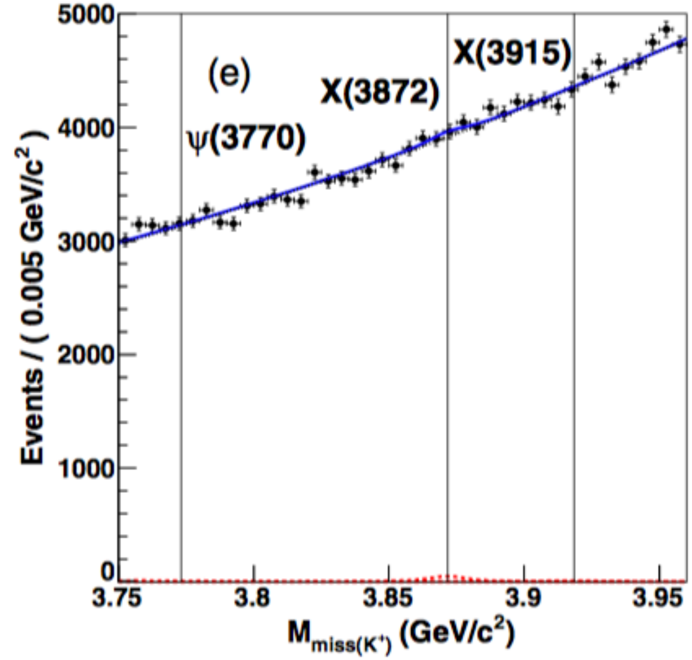


Absolute Brs of X(3872) from Belle

Only the best B tag candidate is retained.

PRD 97, 012005 (2018)





Mode	Yield	Significance (σ)	$\epsilon(10^{-3})$	$\mathcal{B}$ (10^{-4})	World average for $\mathcal{B}$ (10^{-4}) [10]
η_c	2590 ± 180	14.2	2.73 ± 0.02	$12.0 \pm 0.8 \pm 0.7$	9.6 ± 1.1
J/ψ	1860 ± 140	13.7	2.65 ± 0.02	$8.9 \pm 0.6 \pm 0.5$	10.26 ± 0.031
χ_{c0}	430 ± 190	2.2	2.67 ± 0.02	$2.0 \pm 0.9 \pm 0.1$ (<3.3)	$1.50^{+0.15}_{-0.14}$
χ_{c1}	1230 ± 180	6.8	2.68 ± 0.02	$5.8 \pm 0.9 \pm 0.5$	4.79 ± 0.23
$\eta_c(2S)$	1050 ± 240	4.1	2.77 ± 0.02	$4.8 \pm 1.1 \pm 0.3$	3.4 ± 1.8
$\psi(2S)$	1410 ± 210	6.6	2.79 ± 0.02	$6.4 \pm 1.0 \pm 0.4$	6.26 ± 0.24
$\psi(3770)$	-40 ± 310	-	2.76 ± 0.02	$-0.2 \pm 1.4 \pm 0.0$ (<2.3)	4.9 ± 1.3
$X(3872)$	260 ± 230	1.1	2.79 ± 0.01	$1.2 \pm 1.1 \pm 0.1$ (<2.6)	(<3.2)
$X(3915)$	80 ± 350	0.3	2.79 ± 0.01	$0.4 \pm 1.6 \pm 0.0$ (<2.8)	-

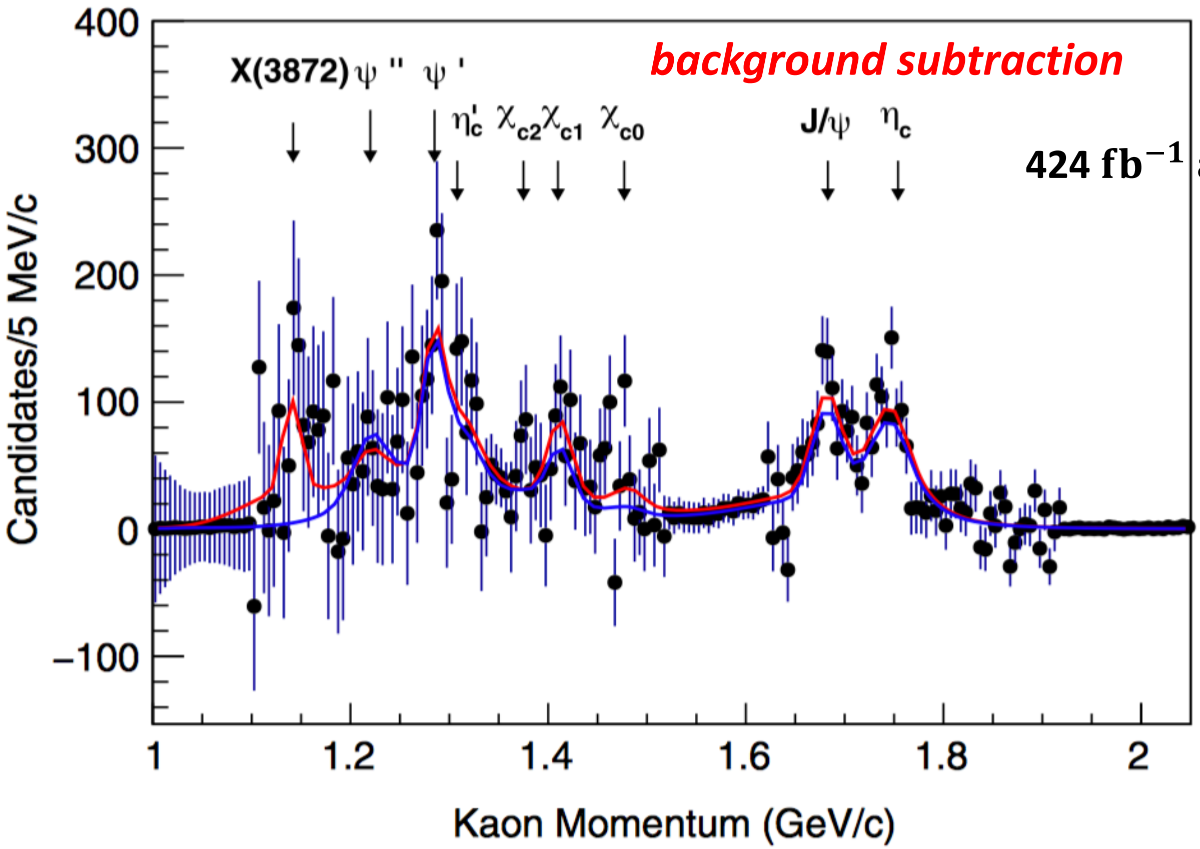
711 fb^{-1} at $\Upsilon(4S)$ resonance
772 $\times 10^6$ $\mathrm{B\overline{B}}$ pairs

The main background comes from secondary kaons from B decays.

Absolute Brs of X(3872) from BaBar

PRL 124, 152001 (2020)

- **If more than one B candidate is found in an event, all candidates are retained to avoid the best one was not the correct one, including those where it belonged to the signal side.**
- **For the X(3872), the efficiency gains up to a factor of 3.**



424 fb^{-1} at $\Upsilon(4S)$ resonance

PRL 122, 222001 (2019)

Particle	Yield	$\mathcal{B}(10^{-4})$	N_σ
J/ψ Reference mode	2364 ± 189	10.1 ± 0.29 (Ref. [21])	10.4
η_c	2259 ± 188	$9.6 \pm 1.2(\text{stat}) \pm 0.6(\text{syst})$	9.3
χ_{c0}	287 ± 181	$2.0 \pm 1.3(\text{stat}) \pm 0.3(\text{syst})$	1.6
χ_{c1}	1035 ± 193	$4.0 \pm 0.8(\text{stat}) \pm 0.6(\text{syst})$	2.2
χ_{c2}	200 ± 164	< 2.0	1.2
$\eta_c(2S)$	527 ± 271	$3.5 \pm 1.7(\text{stat}) \pm 0.5(\text{syst})$	2.3
ψ'	1278 ± 285	$4.6 \pm 1(\text{stat}) \pm 0.7(\text{syst})$	3.1
$\psi(3770)$	497 ± 308	$3.2 \pm 2.0(\text{stat}) \pm 0.5(\text{syst})$	1.2
$X(3872)$	992 ± 285	$2.1 \pm 0.6(\text{stat}) \pm 0.3(\text{syst})$	3.0

- $\mathcal{B}[X(3872) \to J/\psi\pi^+\pi^-]$ = **(4.1±1.3)%**
- **The measurement therefore suggests that the X(3872) has a significant molecular component.**

@CEPC

- We have a large B data samples compared to B-factories (two times larger).

- Running at the Z-pole leads to a much larger boost of B mesons and their decay products. The larger boost leads to a much larger displacement of secondary vertices. The main background comes from secondary kaons from B decays (kaons from D decays) can be suppressed efficiently.

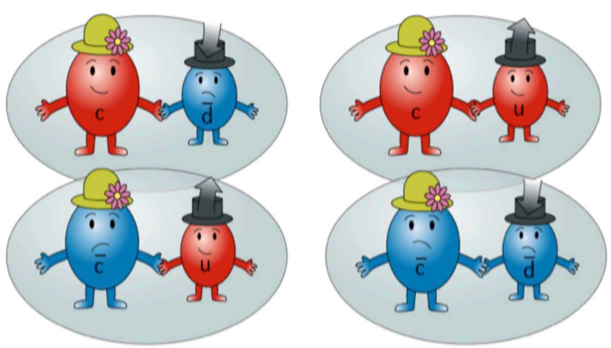
CEPC is very promising to measure the absolute Brs of X(3872), which provides the critical information to distinguish the nature of X(3872).

Pentaquark states with heavy quarks

PRL 115, 112001 (2015)

5 narrow exotic states close to meson-meson thresholds

State	Mass MeV	Width MeV	$Q\bar{Q}$ decay mode	Phase space MeV	Nearby threshold	ΔE MeV
X(3872)	3872	< 1.2	$J/\psi\pi^+\pi^-$	495	$\bar{D}D^*$	<1
$Z_c(3900)$	3900	24 - 46	$J/\psi\pi$	663	$\bar{D}D^*$	24
$Z_c(4020)$	4020	8 - 25	$h_c\pi$	361	$\bar{D}^*D^*$	6
$Z_b(10610)$	10608	21	$\Upsilon\pi$	1008	$\bar{B}B^*$	2 ± 2
$Z_b(10650)$	10651	10	$\Upsilon\pi$	1051	$\bar{B}^*B^*$	2 ± 2
✗	-				$\bar{D}D$	-
✗					$\bar{B}B$	



Molecule Tetraquark

Molecule or tetraqurak?

Belle, PRL 116, 212001 (2016):

$$\frac{\Gamma(Z_b(10610) \to \bar{B}B^*)}{\Gamma(Z_b(10610) \to \Upsilon(1S)\pi)} \approx \frac{86\%}{0.54\%} = \mathcal{O}(100)$$

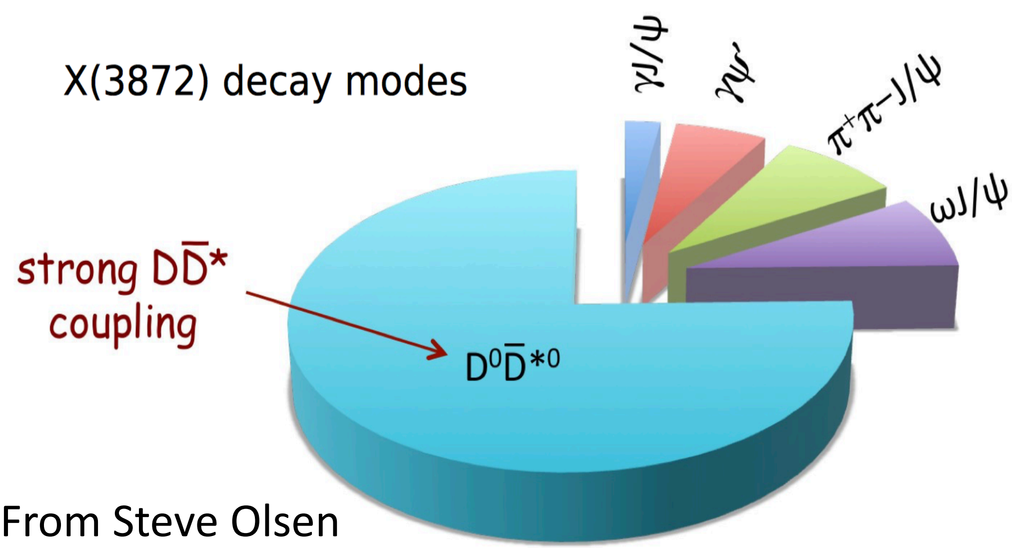
despite 1000 MeV of phase space

for $\Upsilon(1S)\pi$ vs few MeV for $\bar{B}B^*$!

BESIII, PRD 92, 092006 (2015):

$$\frac{\Gamma(Z_c(3900) \to \bar{D}D^*)}{\Gamma(Z_c(3900) \to J/\psi\pi)} \approx 8$$

X(3872) decay modes

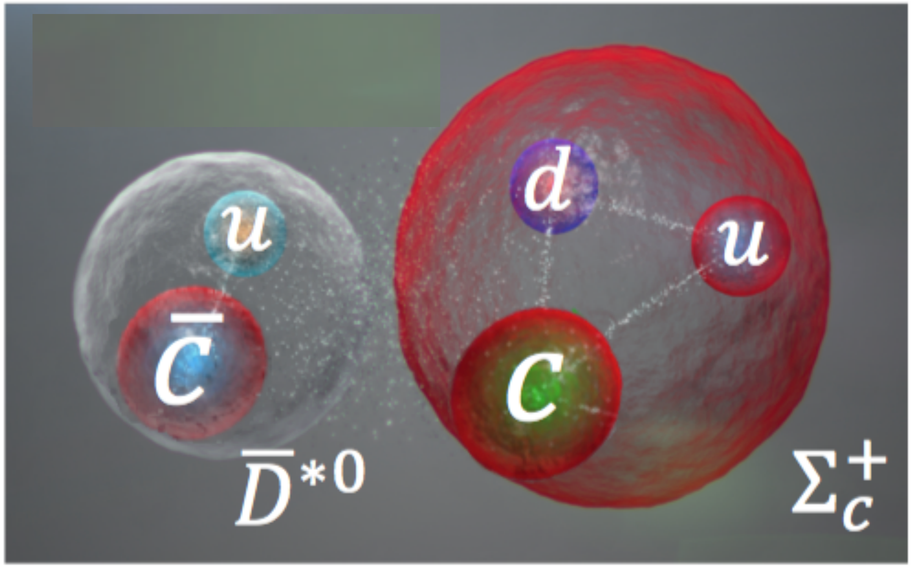


From Steve Olsen

The possible molecular of Z_Q and X(3872)

- **masses near thresholds**
- **Narrow width despite very large phase space**
- **BR(fall part mode) >> BR(quarknium + X)**

Extend to doubly heavy hadronic molecules

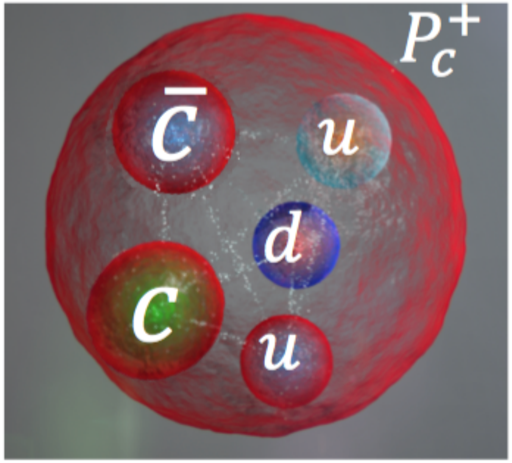


$\mathbf{M(P_c) =}$
$\mathbf{M_{\bar{D}^{*0}} + M_{\Sigma_c^+}}$ **– a few MeV**

PRL 105, 232001 (2010)
PRC 84, 015203 (2011)
CPC36, 6 (2012)
PRC85, 044002 (2012)
PRL 115, 122001 (2015)

Other models:

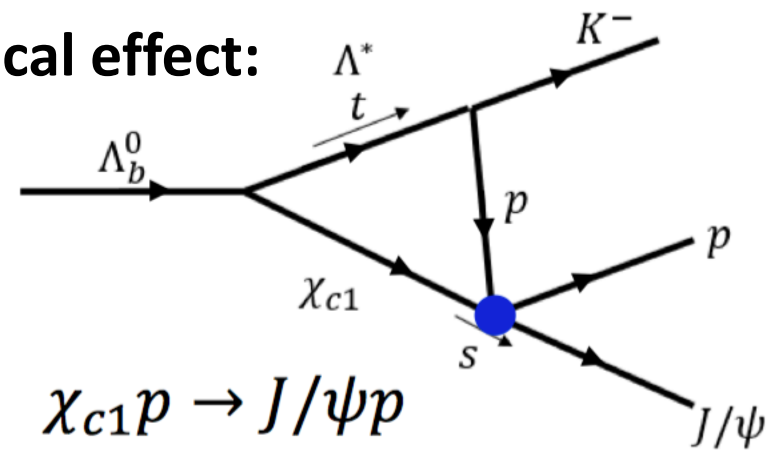
Tightly-bound pentaquark



$\mathbf{\Delta E \sim 400\ MeV}$

PLB 749, 289 (2015)
PLB 749, 454 (2015)
PLB 749, 454 (2015) ?

Kinematical effect:

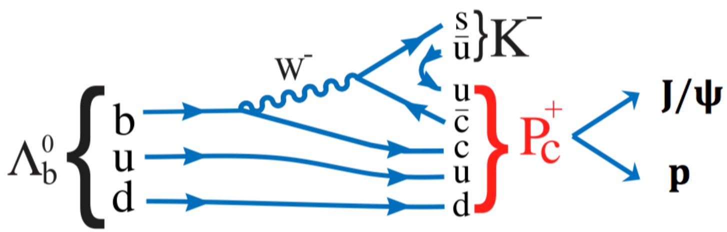


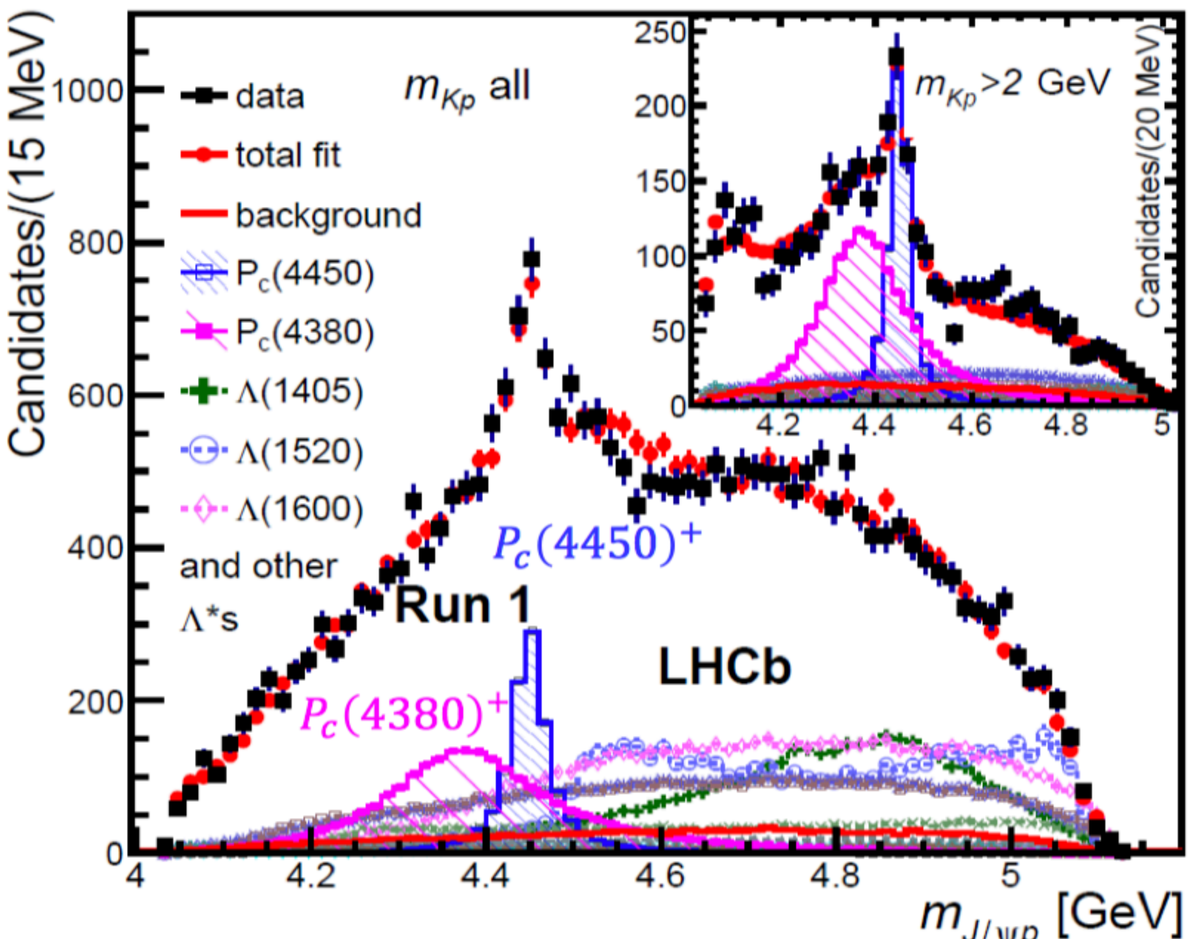
$$\chi_{c1} p \to J/\psi p$$

PRD 92, 071502 (2015)
PLB 757, 231 (2016)
arXiv:1507.06552
PLB 757, 61 (2016)

LHCb observations in 2015

PRL 115, 072001 (2015)





A a full 6D amplitude analysis was performed.

$P_c(4450)$:
M = (4450$\pm$2$\pm$3) MeV/c^2
Γ = (39$\pm$5$\pm$19) MeV/c^2

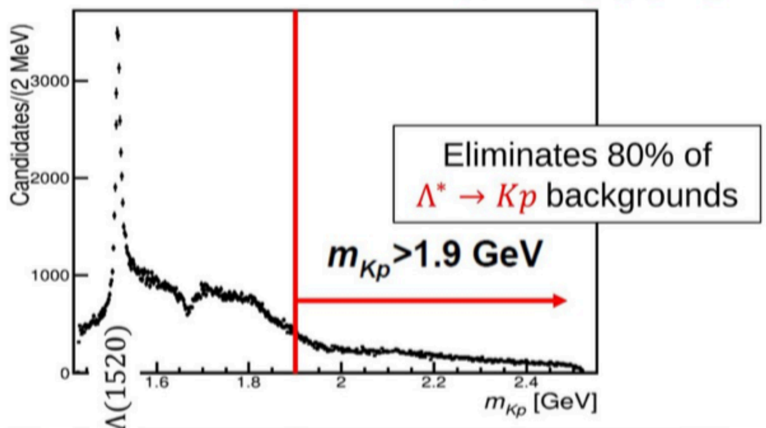
$P_c(4380)$:
M = (4380$\pm$8$\pm$29) MeV/c^2
Γ = (205$\pm$18$\pm$86) MeV/c^2

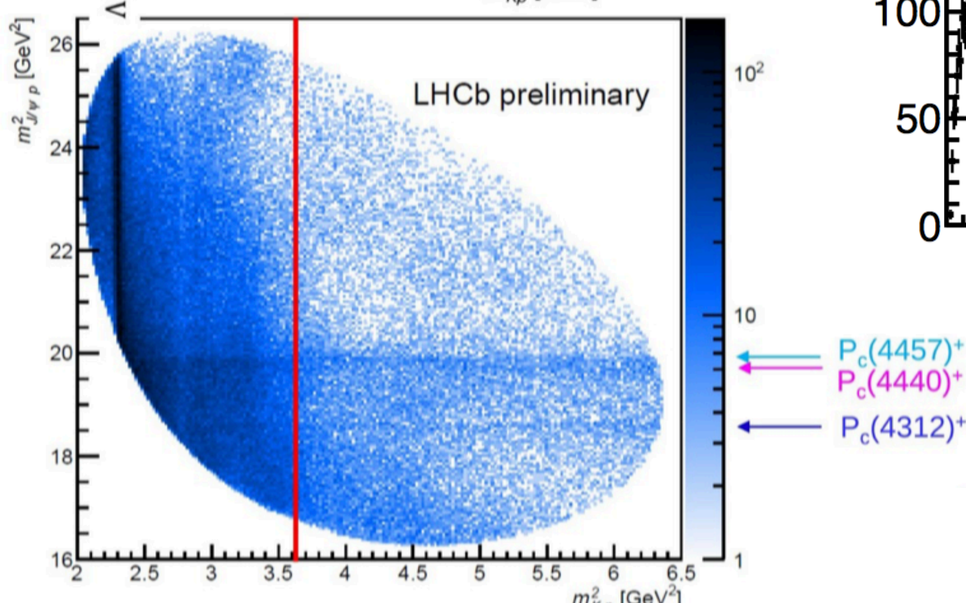
LHCb observations in 2019

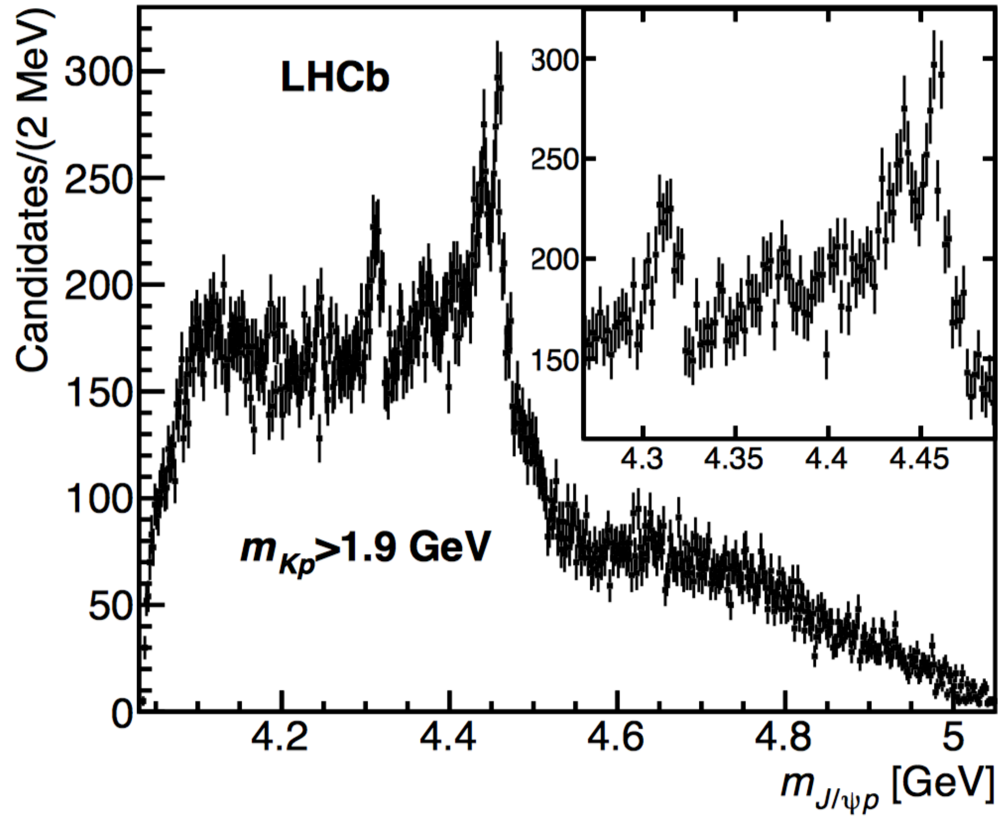
PRL 122, 222001 (2019)

An order of magnitude increases in signal yield

- **Inclusion of Run 2 data (x 5)**
- **Improved data selection (x 2)**







$P_c(4380)$ is splited into two peaks.

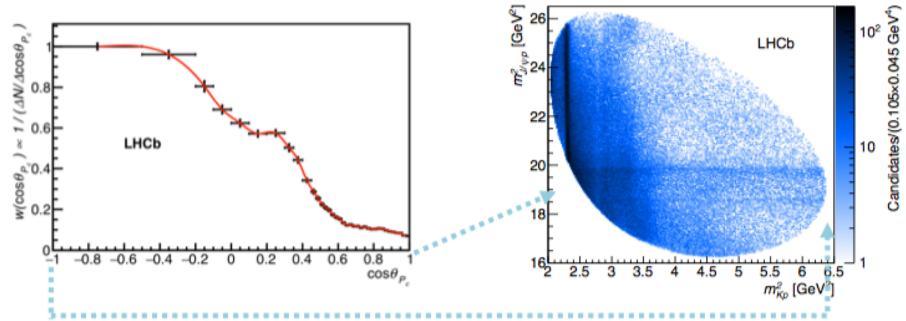
The fitted results

- ➢ **Candidates weighted by *w***

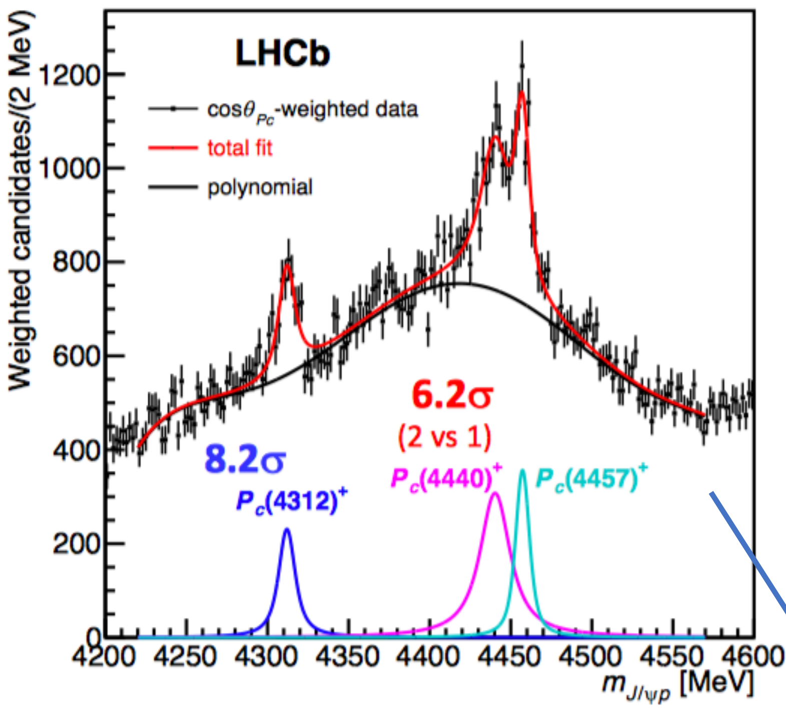
(inverse of $\cos\theta_{P_c}$ distribution of Λ_b^0)

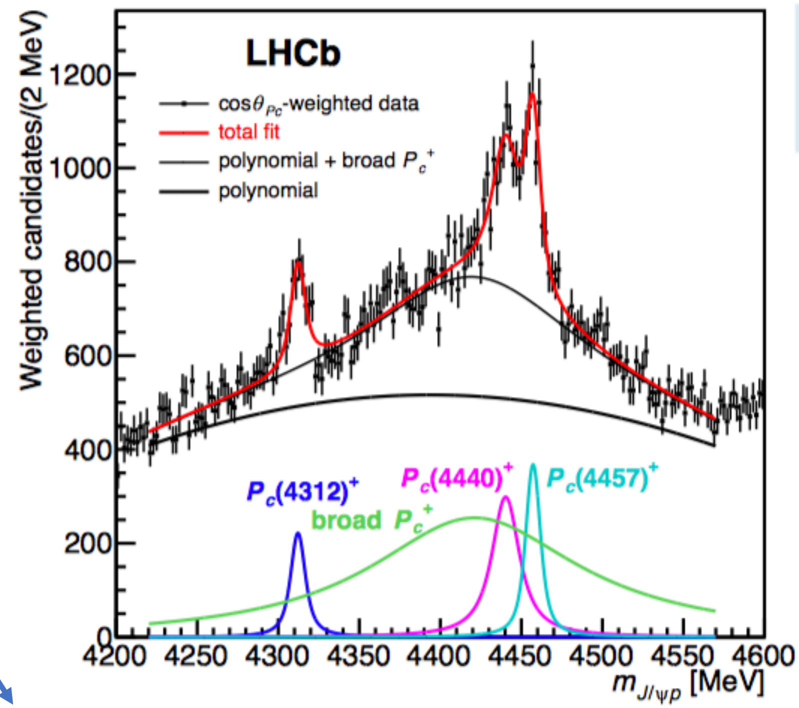
- ➢ **Three BW functions ⊗ resolution**

for signals and higher-order polynomial or low-order polynomial + broad BW for backgrounds



PRL 122, 222001 (2019)





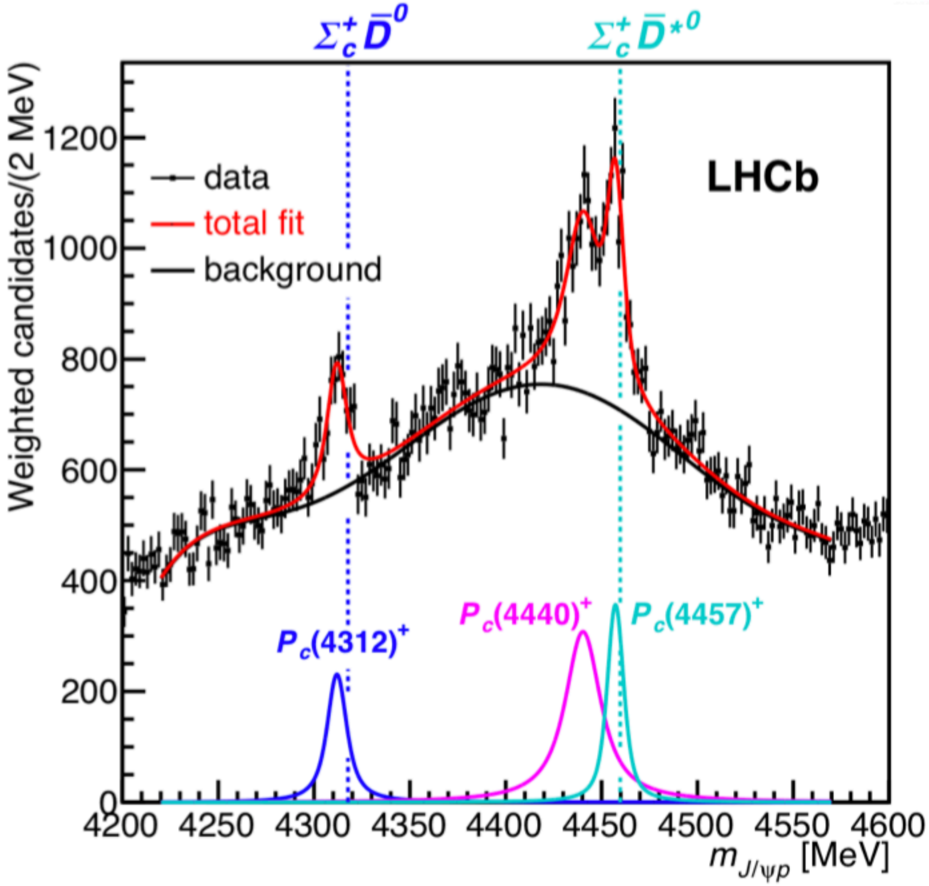
State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

Molecular interpretation

- **The near-threshold masses of $\mathrm{P_c(4450)}$, $\mathrm{P_c(4450)}$, and $\mathrm{P_c(4450)}$ favour "molecular" pentaquarks with meson-baryon substructure.**
- **Regardless of the binding mechanism, the new pentaquarks suggest the existence of a whole new family of such particles.**

PRL 122, 242001 (2019)

Scenario	Molecule	J^P	B (MeV)	M (MeV)
A	$\bar{D}\Sigma_c$	$(1/2)^-$	7.8–9.0	4311.8–4313.0
A	$\bar{D}\Sigma_c^*$	$(3/2)^-$	8.3–9.2	4376.1–4377.0
A	$\bar{D}^*\Sigma_c$	$(1/2)^-$	Input	4440.3
A	$\bar{D}^*\Sigma_c$	$(3/2)^-$	Input	4457.3
A	$\bar{D}^*\Sigma_c^*$	$(1/2)^-$	25.7–26.5	4500.2–4501.0
A	$\bar{D}^*\Sigma_c^*$	$(3/2)^-$	15.9–16.1	4510.6–4510.8
A	$\bar{D}^*\Sigma_c^*$	$(5/2)^-$	3.2–3.5	4523.3–4523.6
B	$\bar{D}\Sigma_c$	$(1/2)^-$	13.1–14.5	4306.3–4307.7
B	$\bar{D}\Sigma_c^*$	$(3/2)^-$	13.6–14.8	4370.5–4371.7
B	$\bar{D}^*\Sigma_c$	$(1/2)^-$	Input	4457.3
B	$\bar{D}^*\Sigma_c$	$(3/2)^-$	Input	4440.3
B	$\bar{D}^*\Sigma_c^*$	$(1/2)^-$	3.1–3.5	4523.2–4523.6
B	$\bar{D}^*\Sigma_c^*$	$(3/2)^-$	10.1–10.2	4516.5–4516.6
B	$\bar{D}^*\Sigma_c^*$	$(5/2)^-$	25.7–26.5	4500.2–4501.0



$\mathrm{J^P}$ measurements and searching for isospin partners are needed.

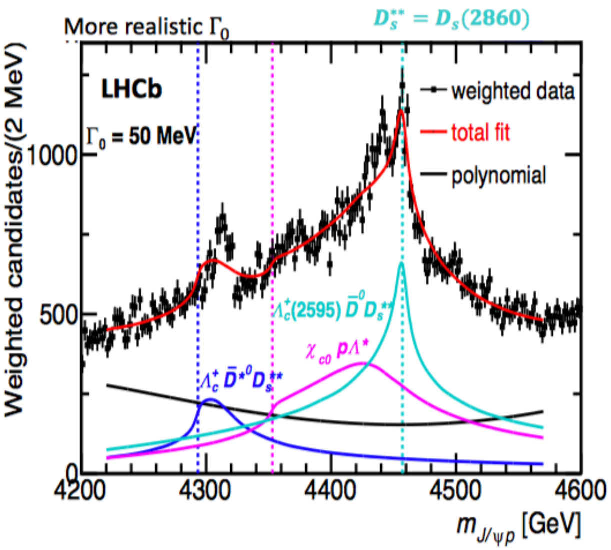
Triangle diagrams

PRL 122, 222001 (2019)

- Can produce peaking structures at or above mass threshold
- Cannot rule out $\mathrm{P_c}(4457)$ as a triangle effect

$P_c(4312)^+$, $P_c(4440)^+$ are too far from any rescattering thresholds

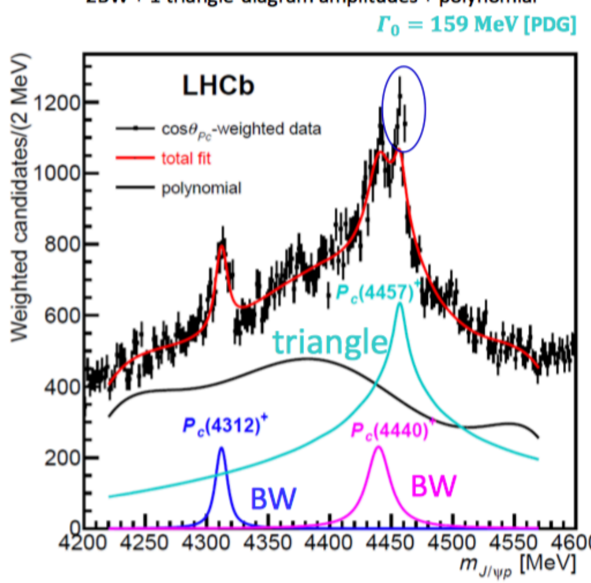
3 triangle-diagram amplitudes + polynomial

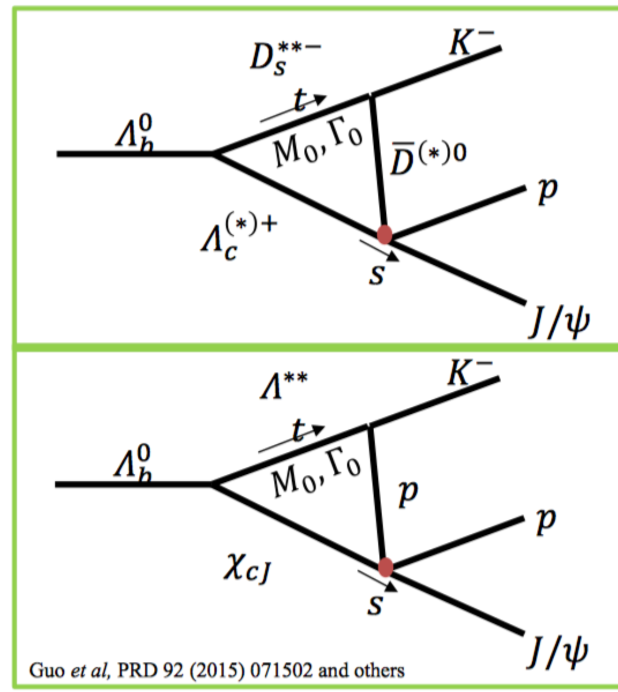


$P_c(4457)^+$ is right at the $\Lambda_c(2595)^+\bar{D}^0$ threshold

2BW + 1 triangle-diagram amplitudes + polynomial

$\Gamma_0 = 159$ MeV [PDG]



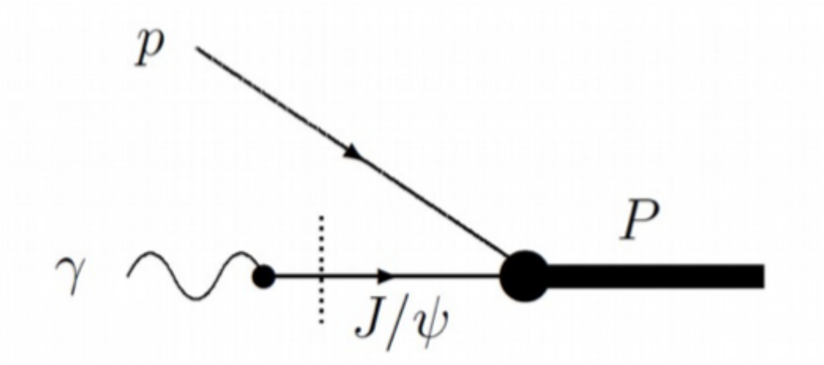


The structure of Pc states is still an open question. [Phys. Rep. 873 (2020) 1–154].

Test via photoproduction

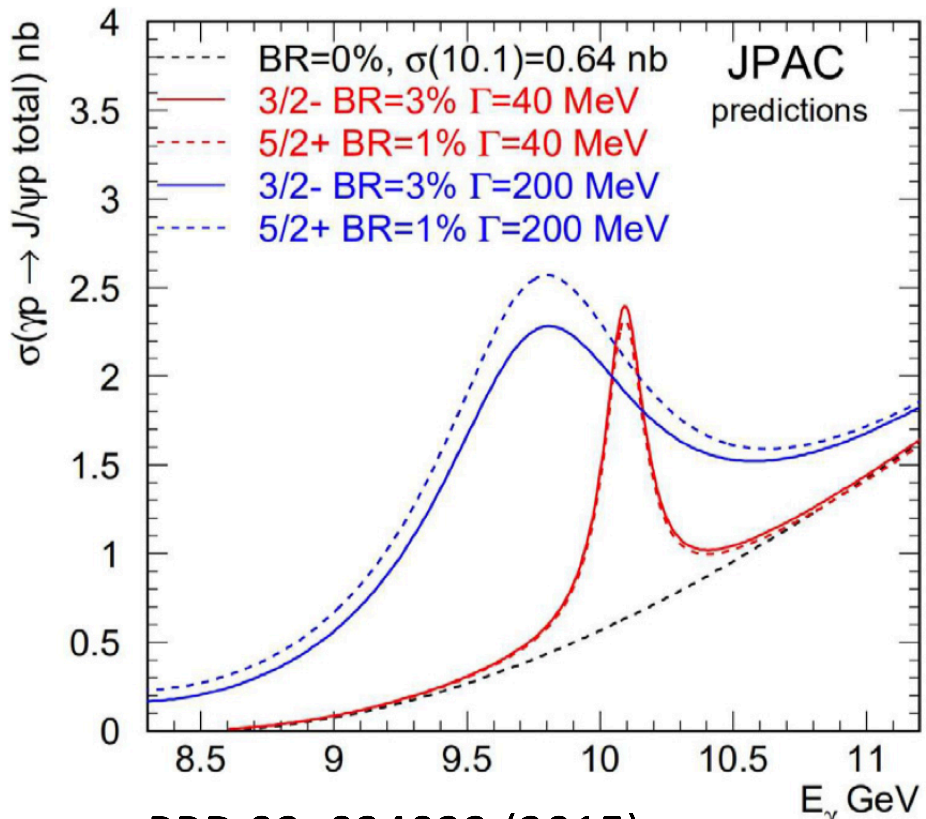
arXiv:1609.00050
PLB 752, 329 (2016)
NPA 978, 201 (2018)
arXiv:1609.00676
PRD 94, 034002 (2016)
PRD 92, 031502 (2015)
arXiv:1703. 06928

One of the most promising ways to independently confirm the pentaquarks.



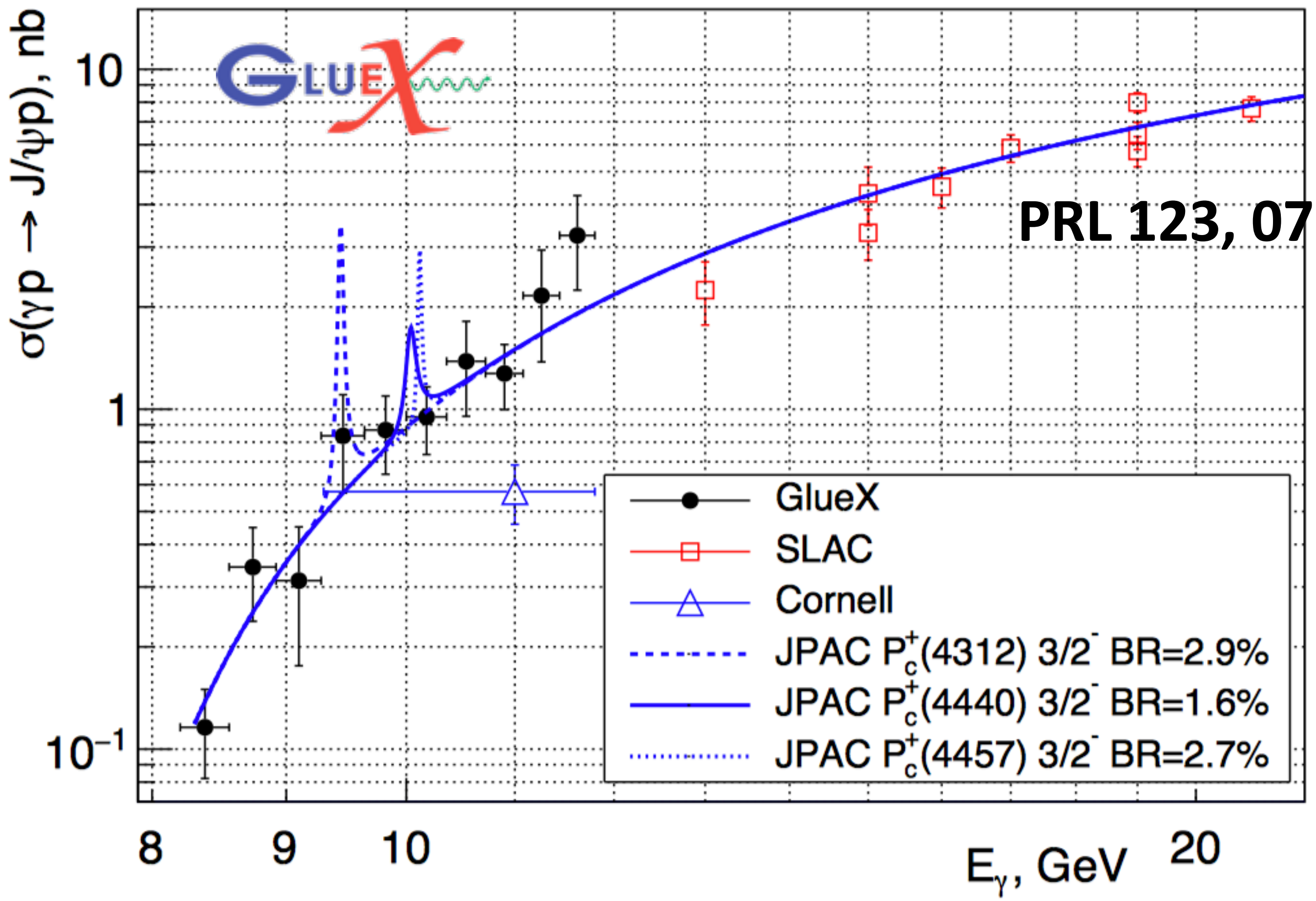
A pentaquark state Pc does exist:

⟹ A peak in the cross sections of $\gamma p \rightarrow J/\psi p$



PRD 92, 034022 (2015)

Test via photoproduction



PRL 123, 072001 (2019)

A less model-dependent limit at 90% C.L.:

$\sigma_{max}(\gamma p \to P_c^+) \times \mathcal{B}(P_c^+ \to J/\psi p)$	
$P_c(4312)^-$	< 4.6 nb^{-1}
$P_c(4440)^-$	< 1.8 nb^{-1}
$P_c(4457)^-$	< 3.9 nb^{-1}

@CEPC

To understand exotic pentaquarks further:

- **Confirm $\mathrm{P_c(4450)/P_c(4450)/P_c(4450)} \rightarrow J/\psi p$ from LHCb, and detailed amplitude analysis to determine $\mathrm{J^P}$**
- **More decay modes:**

1) in B decays: $\mathrm{B^0 \rightarrow p\bar{p}K^0}$, $\mathrm{\bar{B}^0 \rightarrow p\bar{p}D^0}$

2) in baryon decays: $\mathrm{\Lambda_c^+ \rightarrow pK^0\bar{K}^0}$, $\mathrm{\Lambda_b^+ \rightarrow K^-\chi_{c1}p}$, $\mathrm{\Xi_b^0 \rightarrow pD^0K^-}$, $\mathrm{\Xi_b^0 \rightarrow J/\psi\Lambda K^-}$

3) in $\mathrm{e^+e^-}$ continuum processes: $\mathrm{e^+e^- \rightarrow J/\psi p}$ + X, $\mathrm{\chi_{c1}p}$ + X, $\mathrm{\Sigma_c^+\bar{D}^0}$, $\mathrm{\Sigma_c^{*+}\bar{D}^0}$ …

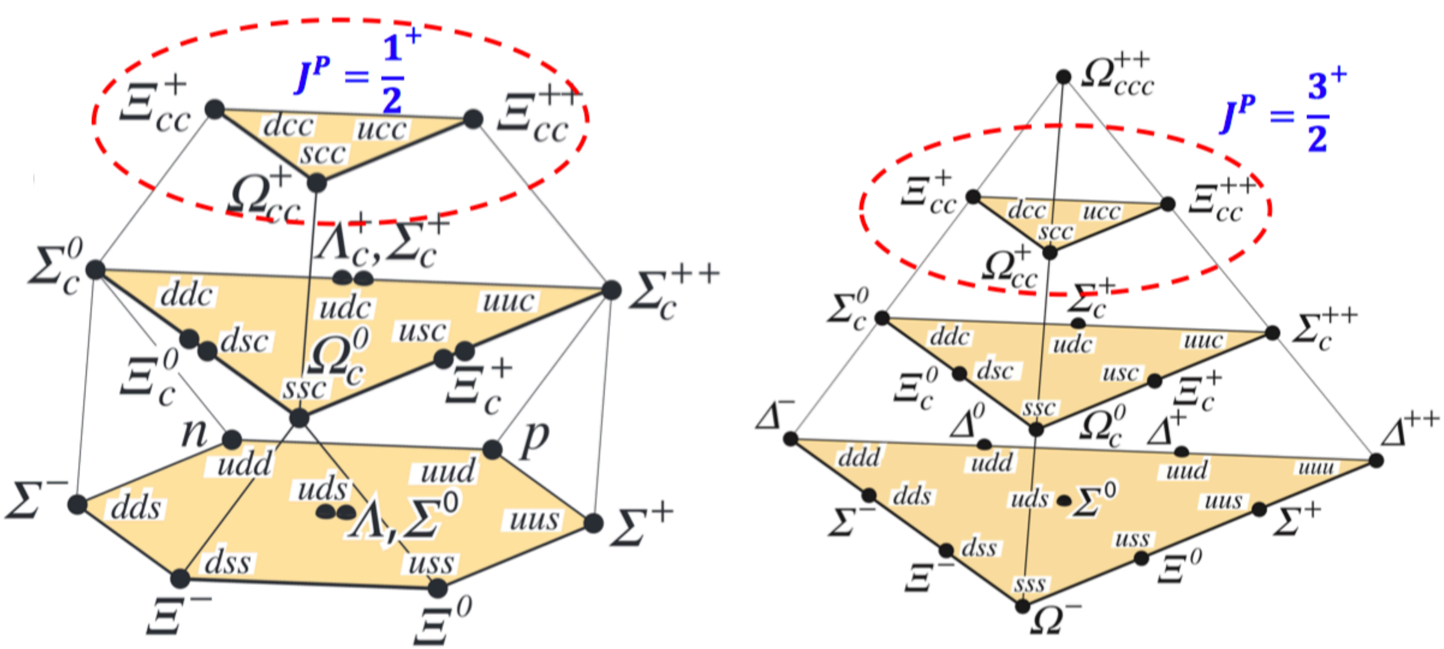
Physics Reports 873 (2020) 1–154

Doubly heavy baryons in charm and beauty

Doubly-charmed baryons

- Multiplets of baryon and meson states composed of the lightest four quarks (u, d, s, c) form SU(4) multiplets [PRD 12, 147 (1975)].
- A SU(3) triplet with two charm quarks: Ξ_{cc}^{+}(dcc), Ξ_{cc}^{++}(ucc), and Ω_{cc}^{+}(scc).

From L. M. Zhang, HADRON 2019 conference



- $J^P = \frac{1}{2} \rightarrow J^P = \frac{1}{2}$ via strong/electromagnetic processes
- $J^P = \frac{3}{2} \rightarrow J^P = \frac{1}{2}$ with a *c* quark transformed to lighter quarks

Doubly heavy baryons QQq:
ccq, bcq, bbq, $q = u,d$
should also exist.

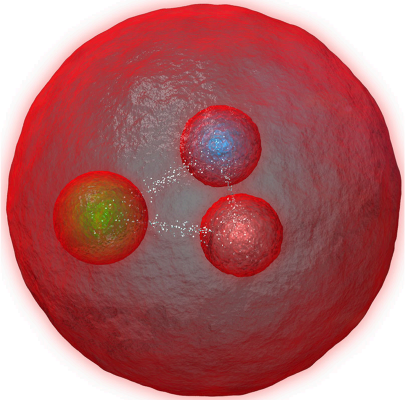


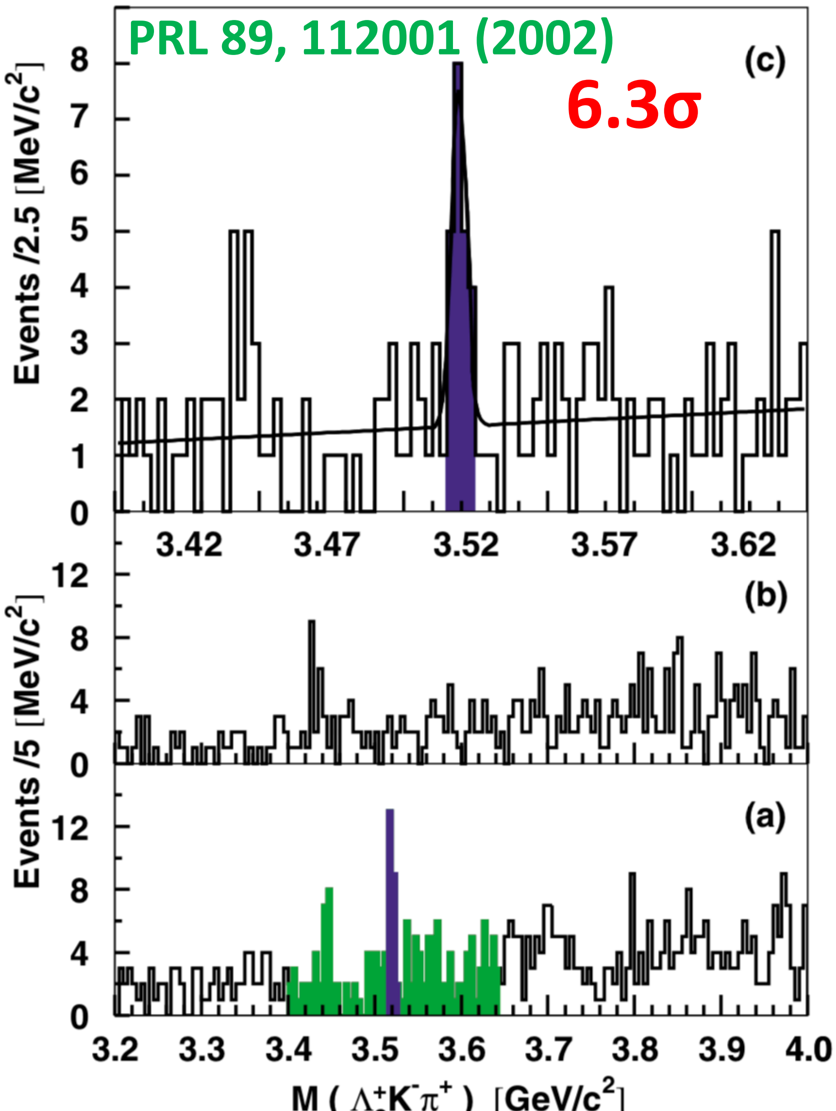
TABLE XVIII. Summary of our mass predictions (in MeV) for lowest-lying baryons with two heavy quarks. States without a star have $J = 1/2$; states with a star are their $J = 3/2$ hyperfine partners. The quark q can be either u or d. The square or curved brackets around cq denote coupling to spin 0 or 1. PRD 90, 094007 (2014)

State	Quark content	$M(J = 1/2)$	$M(J = 3/2)$
$\Xi_{cc}^{(*)}$	ccq	3627 ± 12	3690 ± 12
$\Xi_{bc}^{(*)}$	$b[cq]$	6914 ± 13	6969 ± 14
Ξ'_{bc}	$b(cq)$	6933 ± 12	$\cdots$
$\Xi_{bb}^{(*)}$	bbq	10162 ± 12	10184 ± 12

Baryons with two heavy quarks provide a unique system to test QCD since the heavy quarks are nearly static and act as a center of gravity for the hadron.

Ξ_{cc}^{+} by SELEX

SELEX collides high energy hyperon beams (Σ) with nuclear targets (*p*).



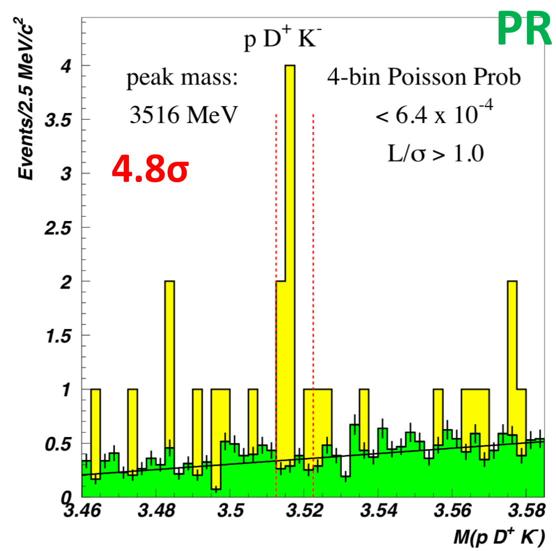
Mass: (3519$\pm$1) MeV/c^2

Width: consistent with zero

Lifetime: < 33 fs at 90% C.L.

$$\frac{\sigma(\Xi_{cc}^{+})\times\mathcal{B}(\Xi_{cc}^{+}\to\Lambda_c^{+}K^{-}\pi^{+})}{\sigma(\Lambda_c^{+})}\sim 20\%$$

PRB 628, 18 (2005)

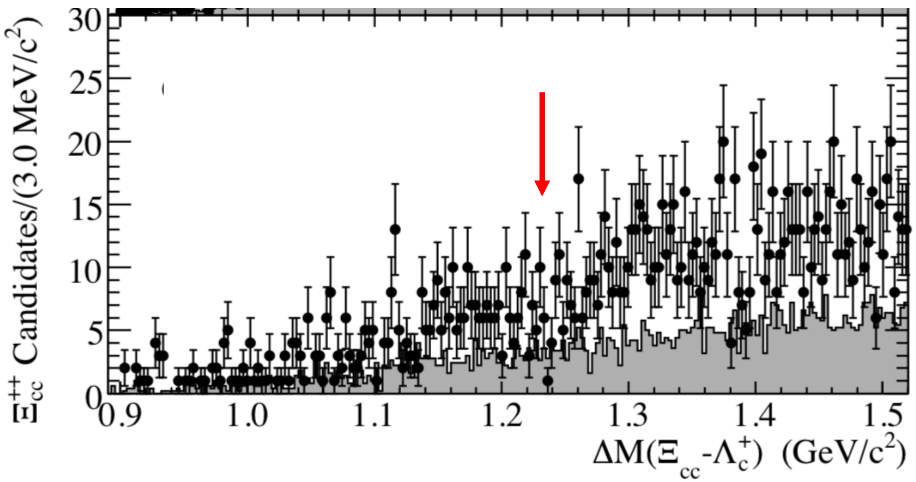


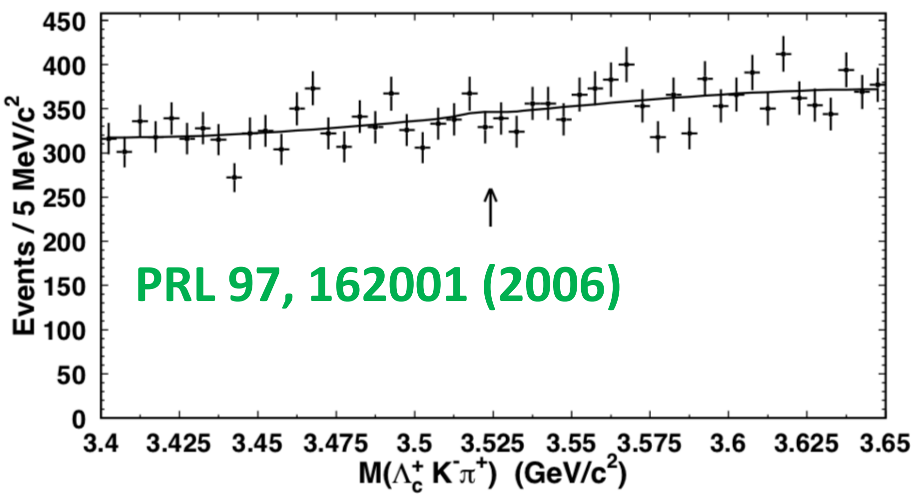
$$\frac{\Gamma(\Xi_{cc}^{+}\to pD^{+}K^{-})}{\Gamma(\Xi_{cc}^{+}\to\Lambda_c^{+}K^{-}\pi^{+})}$$

=0.36$\pm$0.21

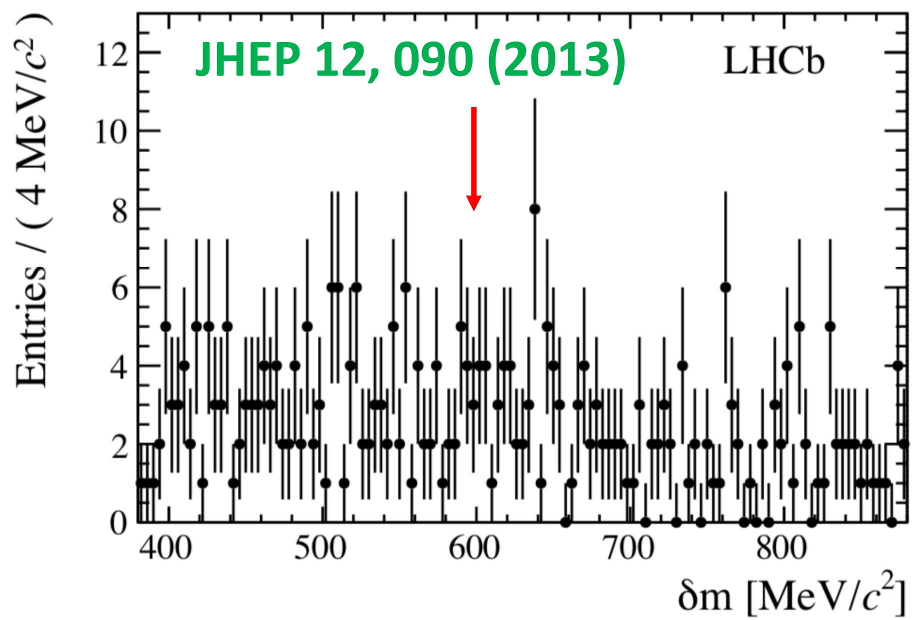
The results are not confirmed by Babar, Belle, and LHCb.

PRD 74, 011103 (2006)





$$\delta m \equiv m([pK^-\pi^+]_{\Lambda_c}K^-\pi^+) - m([pK^-\pi^+]_{\Lambda_c}) - m(K^-) - m(\pi^+)$$



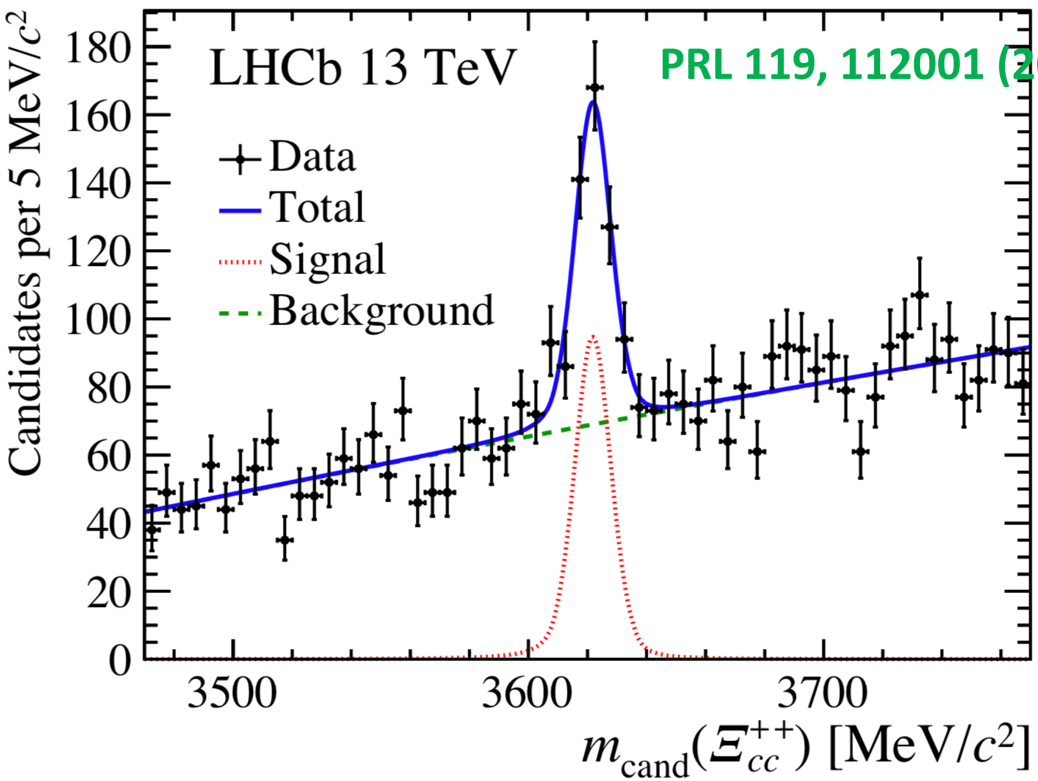
$$\frac{\sigma(\Xi_{cc}^+)\times\mathcal{B}(\Xi_{cc}^+\to\Lambda_c^+K^-\pi^+)}{\sigma(\Lambda_c^+)} < 3.9\times10^{-4}$$

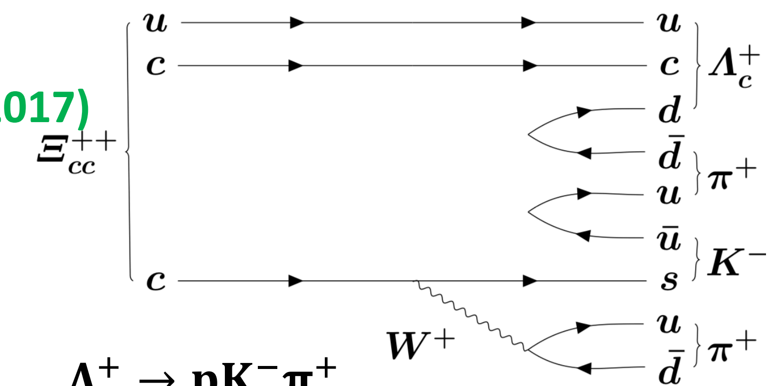
However, the production environments are different between SELEX and other experiments.

$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ by LHCb

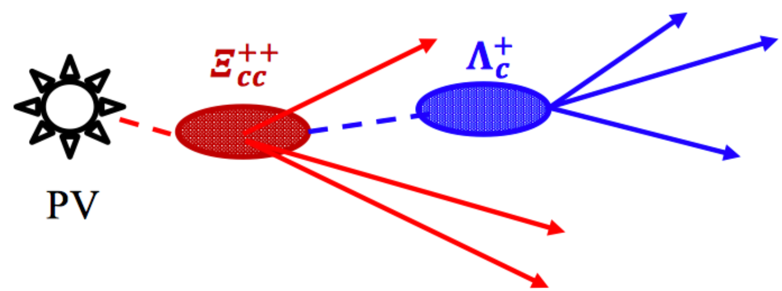
- The long-distance contributions are significantly enhanced compared to Ξ_{cc}^{+}.
- The favorable mode: $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$(Br ~ 10%) CPC 42, 051001 (2018)

$\sqrt{s}$ = 13 TeV, 1.7 fb^{-1} pp collisions data





$\Lambda_c^+ \to p K^- \pi^+$



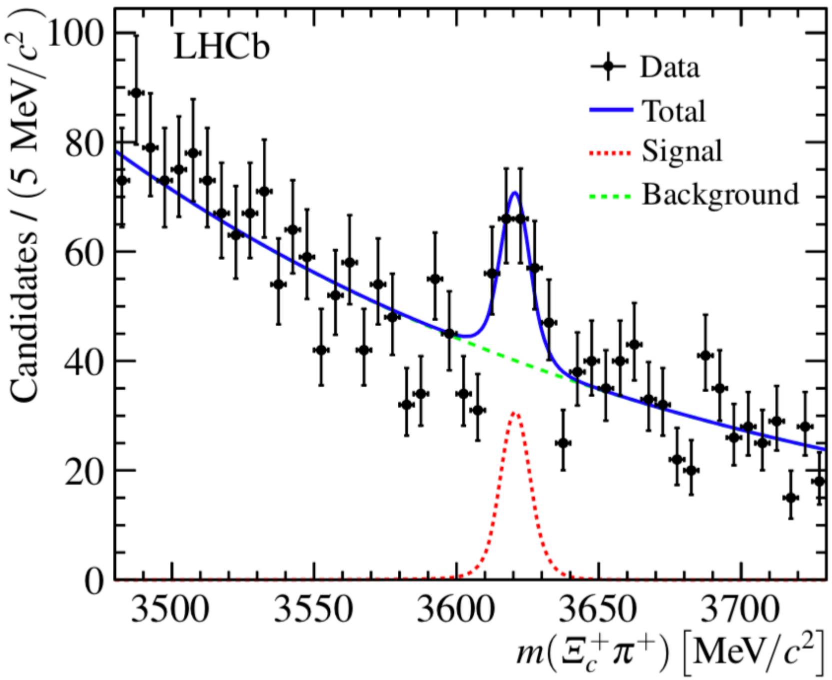
Ξ_{cc}^{++} mass: 3621.40$\pm$0.72(stat)$\pm$0.27(syst)$\pm$0.14(Λ_c^+) MeV/c^2

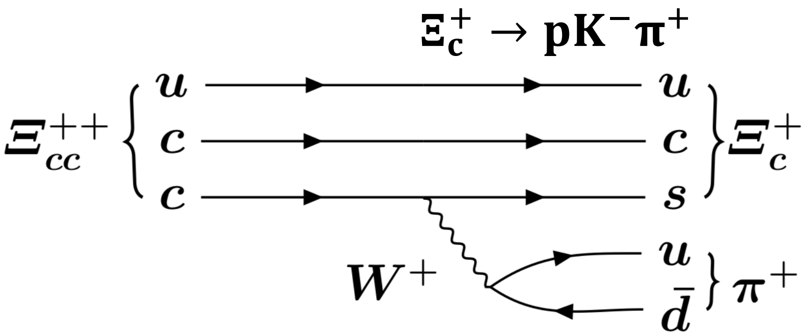
~100 MeV above Ξ_{cc}^{+} peak by SELEX

Width: consistent with zero

$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ by LHCb

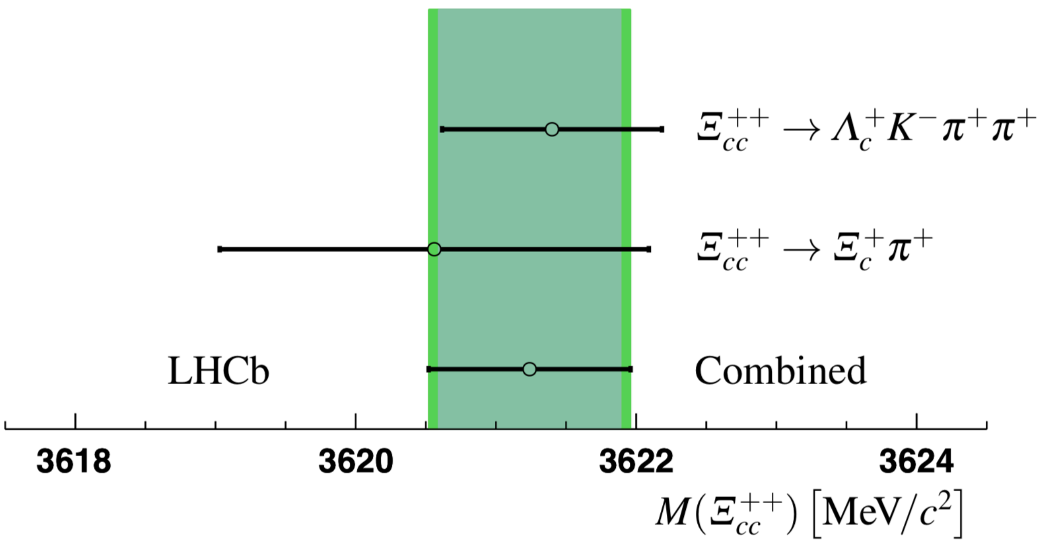
PRL 121, 162002 (2018)





$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+K^-\pi^+\pi^+)} = 0.49 \pm 0.13 \pm 0.24(\Xi_c^+)$$

3621.24 ± 0.65 ± 0.31 MeV



Mass difference:
$m(\Xi_{cc}^{++})$LHCb - $m(\Xi_{cc}^{+})$SELEX =
(103 ± 2) MeV

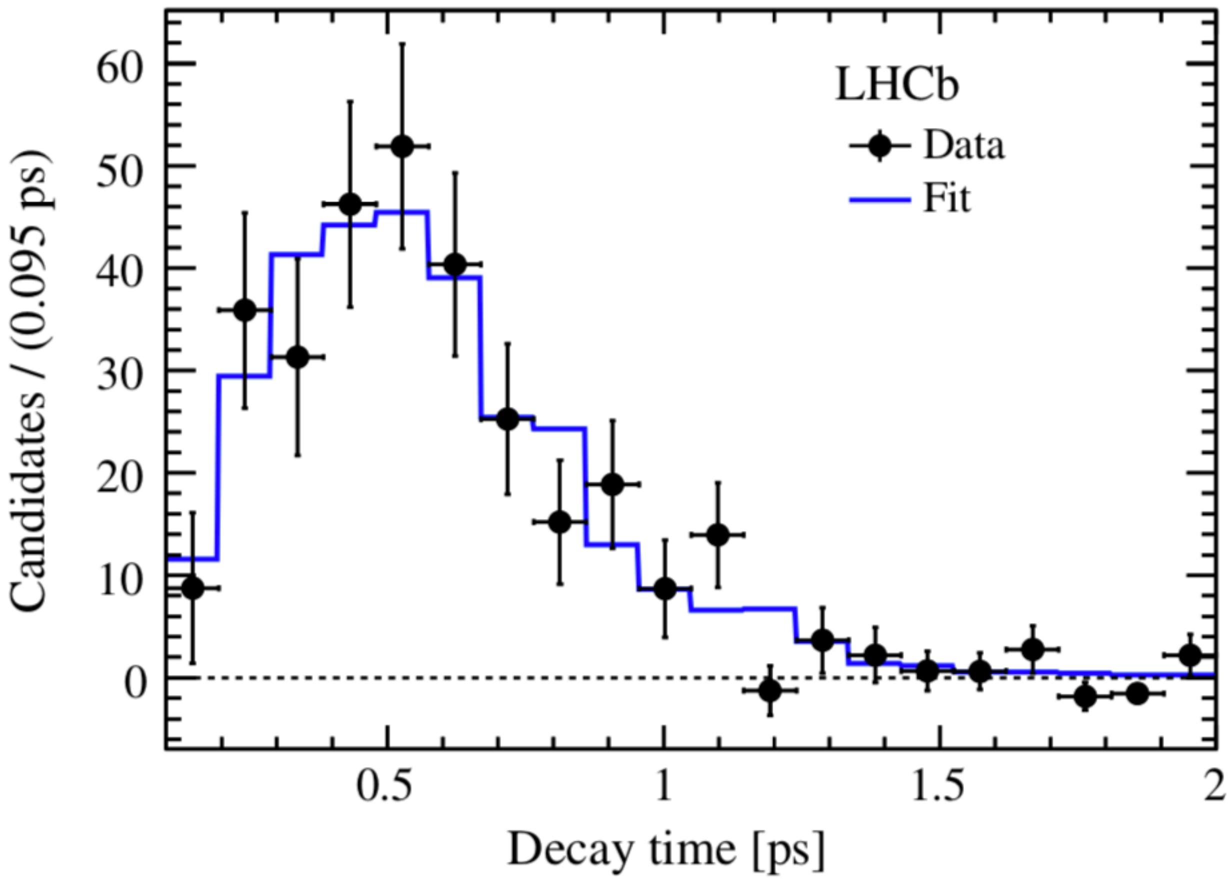
Inconsistent with being isospin partners

The lifetime of Ξ_{cc}^{++}

$$f_{\Xi_{cc}^{++}}(t) = H_{\Lambda_b^0}(t) \times \frac{\epsilon_{\Xi_{cc}^{++}}(t)}{\epsilon_{\Lambda_b^0}(t)} \times \exp\left(\frac{t}{\tau(\Lambda_b^0)} - \frac{t}{\tau(\Xi_{cc}^{++})}\right)$$

Use $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ control sample

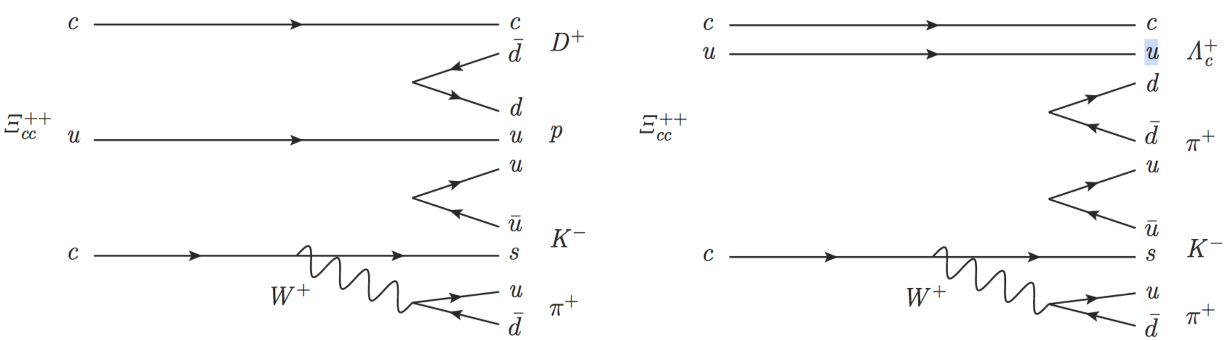
PRL 121, 052002 (2018)



$0.256^{+0.024}_{-0.022}$(stat)$\pm$0.014(syst) ps

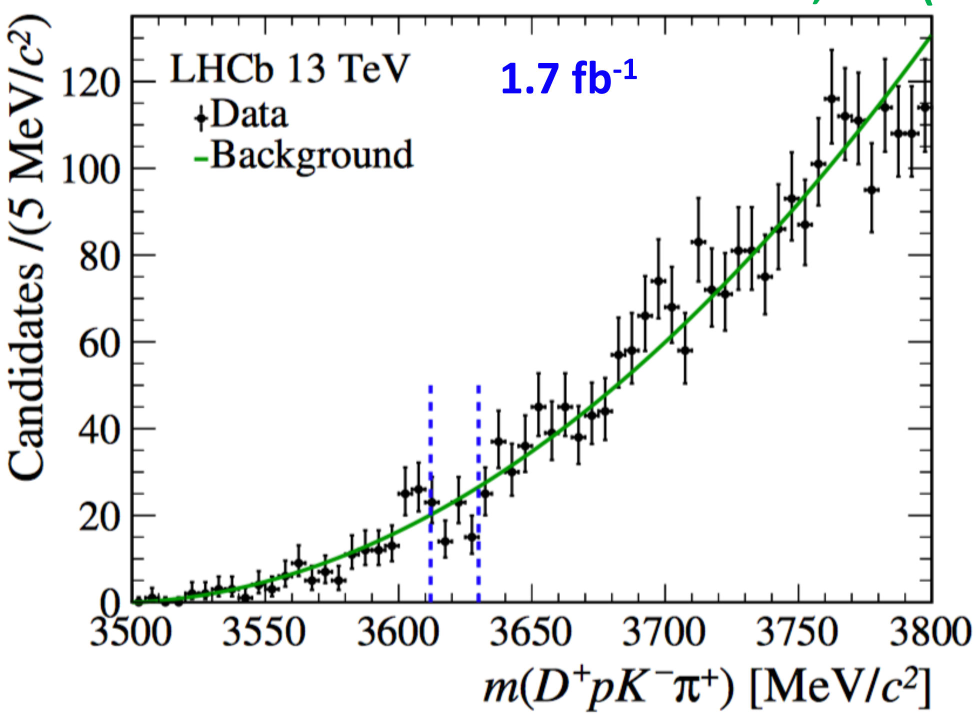
Search for $\Xi_{cc}^{++} \to D^- p K^- \pi^+$

Just swap u and c quarks



- The branching fractions could be comparable.
- The efficiencies are also similar.

JHEP 10, 124 (2019)



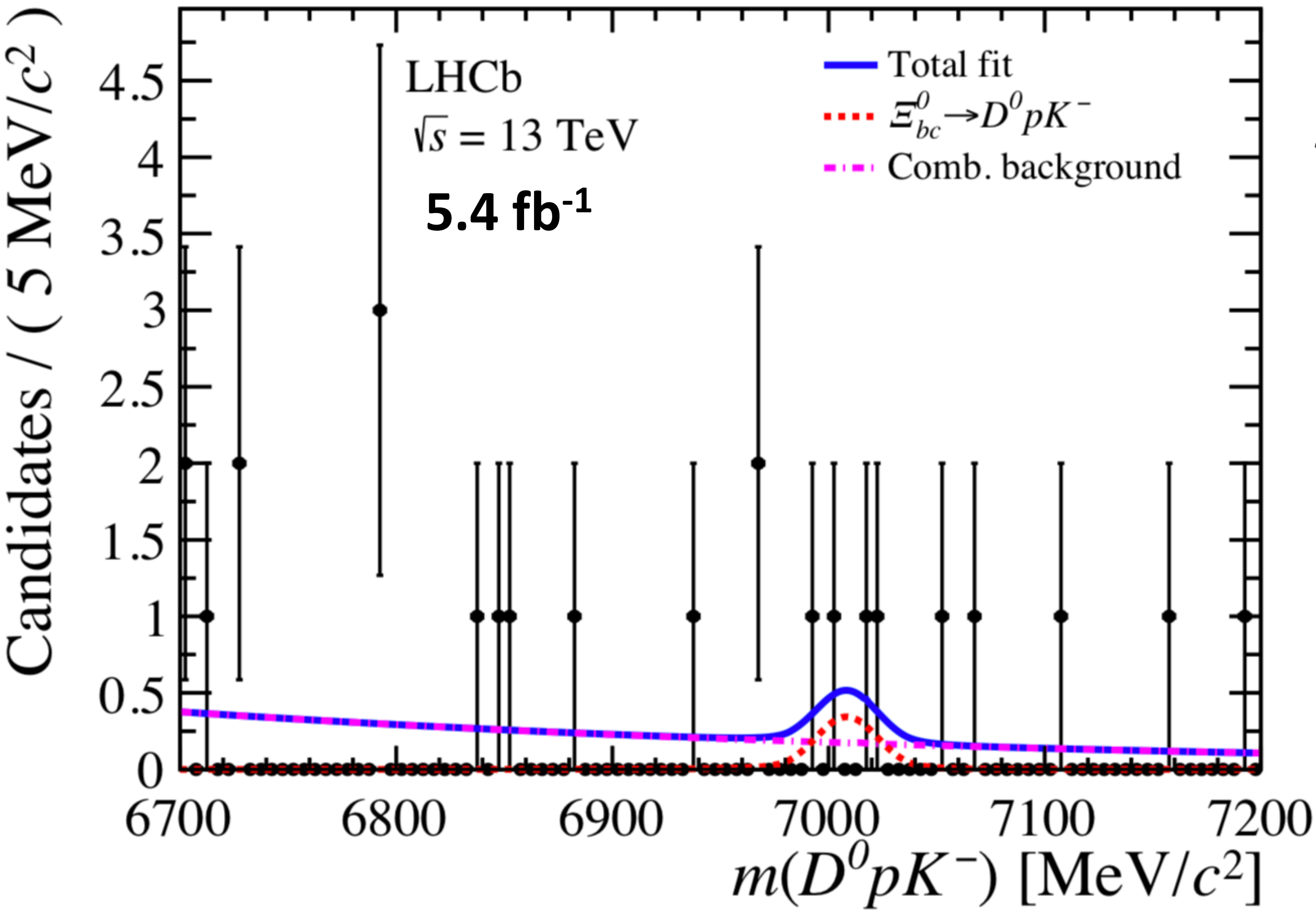
Very stringent upper limit is obtained:

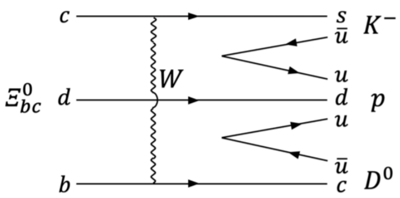
$$R = \frac{\mathcal{B}(\Xi_{cc}^{++} \to D^- p K^- \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)}$$

< 1.7% (2.1%) at 90% (95%) C.L.

Search for $\Xi_{bc}^0 \to D^0pK^-$

arXiv:2009.02481 (2020)





No excess is observed in the full Ξ_{bc}^0 mass range.

Stable doubly heavy tetraquark

Inspired by observation of Ξ_{cc}^{++}, stable doubly heavy tetraquark states are predicted [PRL 119, 202001 (2017), PRL 119, 202002 (2017), Prog.Part.Nucl.Phys. 107, 237 (2019)].

Stable $T(bb\bar{u}\bar{d})$ state [PRL 119, 202001 (2017)]:

- $(bb\bar{u}\bar{d})$: $J^P = 1^+$, 10389±12 MeV, 215 MeV below BB* threshold.
- $(bb\bar{u}\bar{d}) \to \bar{B}D\pi^-$, $J/\psi\bar{K}\bar{B}$, $J/\psi J/\psi K^-\bar{K}^0$, D^0B^-
- $(bc\bar{u}\bar{d})$: $J^P = 0^+$, 7134±13 MeV, 11 MeV below $D^0\bar{B}^0$ threshold.
- $(cc\bar{u}\bar{d})$: $J^P = 1^+$, 3882±12 MeV, 7 MeV above D^0D^{*+} threshold.

Expectations for the ground-state tetraquark states [PRL 119, 202002 (2017)].

State	J^P	j_ℓ	$m(Q_iQ_jq_m)$ (c.g.)	HQS relation	$m(Q_iQ_j\bar{q}_k\bar{q}_l)$	Decay channel	$\mathcal{Q}$ (MeV)
$\{cc\}[\bar{u}\,\bar{d}]$	1^+	0	3663[b]	$m(\{cc\}u)+315$	3978	D^+D^{*0} 3876	102
$\{cc\}[\bar{q}_k\bar{s}]$	1^+	0	3764[c]	$m(\{cc\}s)+392$	4156	$D^+D_s^{*-}$ 3977	179
$\{cc\}\{\bar{q}_k\bar{q}_l\}$	$0^+,1^+,2^+$	1	3663	$m(\{cc\}u)+526$	4146,4167,4210	D^+D^0, D^+D^{*0} 3734,3876	412,292,476
$[bc][\bar{u}\,\bar{d}]$	0^+	0	6914	$m([bc]u)+315$	7229	B^-D^+/B^0D^0 7146	83
$[bc][\bar{q}_k\bar{s}]$	0^+	0	7010[d]	$m([bc]s)+392$	7406	B_sD 7236	170
$[bc]\{\bar{q}_k\bar{q}_l\}$	1^+	1	6914	$m([bc]u)+526$	7439	B^*D/BD^* 7190/7290	249
$\{bc\}[\bar{u}\,\bar{d}]$	1^+	0	6957	$m(\{bc\}u)+315$	7272	B^*D/BD^* 7190/7290	82
$\{bc\}[\bar{q}_k\bar{s}]$	1^+	0	7053[d]	$m(\{bc\}s)+392$	7445	DB_s^* 7282	163
$\{bc\}\{\bar{q}_k\bar{q}_l\}$	$0^+,1^+,2^+$	1	6957	$m(\{bc\}u)+526$	7461,7472,7493	BD/B^*D 7146/7190	317,282,349
$\{bb\}[\bar{u}\,\bar{d}]$	1^+	0	10 176	$m(\{bb\}u)+306$	10 482	$B^-\bar{B}^{*0}$ 10 603	$\boxed{-121}$
$\{bb\}[\bar{q}_k\bar{s}]$	1^+	0	10 252[c]	$m(\{bb\}s)+391$	10 643	$\bar{B}\bar{B}_s^*/\bar{B}_s\bar{B}^*$ 10 695/10 691	$\boxed{-48}$
$\{bb\}\{\bar{q}_k\bar{q}_l\}$	$0^+,1^+,2^+$	1	10 176	$m(\{bb\}u)+512$	10 674,10 681,10 695	B^-B^0, B^-B^{*0} 10 559,10 603	115,78,136

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- Confirm $\Xi_{cc}^{+} \rightarrow pD^{+}K^{-}$ and $\Xi_{cc}^{+} \rightarrow \Lambda_{c}^{+}K^{-}\pi^{+}$ from SELEX
- Confirm $\Xi_{cc}^{++} \rightarrow \Lambda_{c}^{+}K^{-}\pi^{+}\pi^{+}$ and $\Xi_{cc}^{++} \rightarrow \Xi_{c}^{+}\pi^{+}$ from LHCb
- Search for Ω_{cc}^{+}(scc), Ξ_{bc}(bcq), and Ξ_{bb}(bbq)
- Search for a stable doubly heavy tetraquark in BB* decay mode

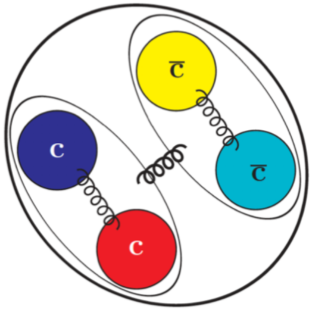
Lifetime: $3\tau(\Xi_{cc}^{+}) \approx 3\tau(\Omega_{cc}^{+}) \approx \tau(\Xi_{cc}^{++})$

- The increase backgrounds with shorter lifetime
- But should be promising at CEPC because of a larger boost and a clean environment

Heavy tetraquarks $QQ\bar{Q}\bar{Q}$

Motivation

- **Many QCD-motivated phenomenological models also predict the existence of states consisting of four heavy quarks, i.e. $T_{Q_1Q_2\bar{Q}_3\bar{Q}_4}$, where Q_i is a c or a b quark [Phys. Lett. 8 (1964) 214, Version 1 CERN-TH-401, CERN, Geneva, 1964].**



- **Tend to be compactly bounded since the interaction between heavy quarks is dominantly mediated by short-range gluon exchange.**

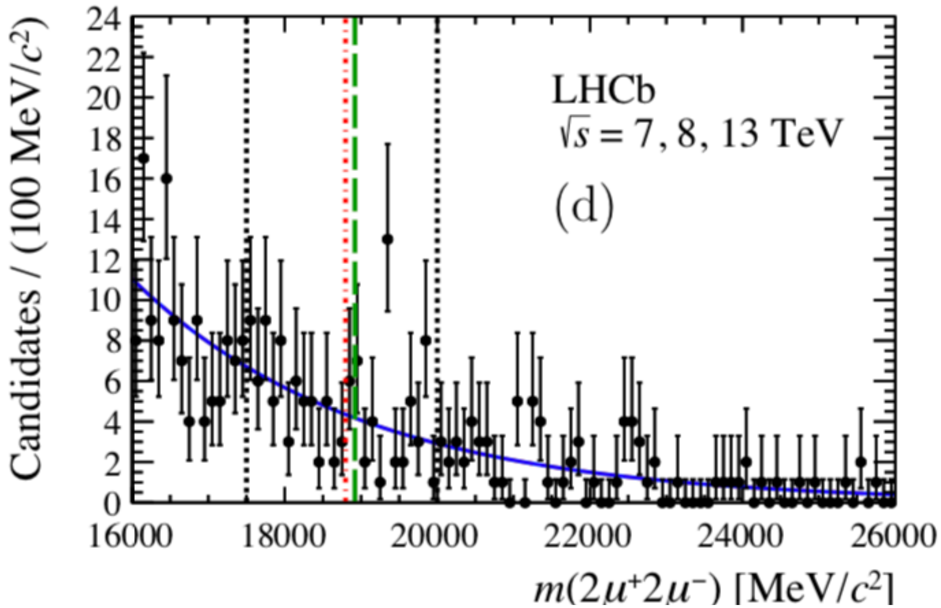
- **The internal structure of such states usually assumes the formation of a diquark (Q_1Q_2) and an anti-diquark $(\bar{Q}_3\bar{Q}_4)$ attracting each other.**

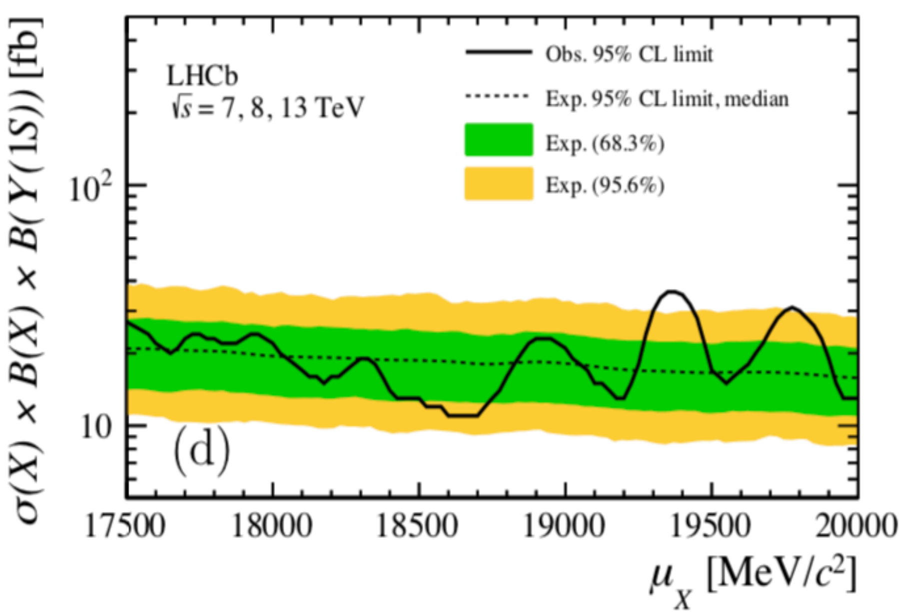
Search for $T_{b\bar{b}b\bar{b}}$ by LHCb

JHEP 1810 (2018) 086

- For $T_{b\bar{b}b\bar{b}} \to \Upsilon(1S)\mu^+\mu^-$ decay, the $\Upsilon(1S)(\to \mu^+\mu^-)$ candidates are combined with an additional dimuon pair with a good vertex-fit quality.
- Rapidities in the range [2.0,4.5] and p_T less than 15 GeV/c.

$\sqrt{s}$ = 7, 8, and 13 TeV, 6.3 fb^{-1} pp collisions data





$$S \equiv \sigma(pp \to X) \times \mathcal{B}(X \to \Upsilon(1S)\mu^+\mu^-) \times \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)$$

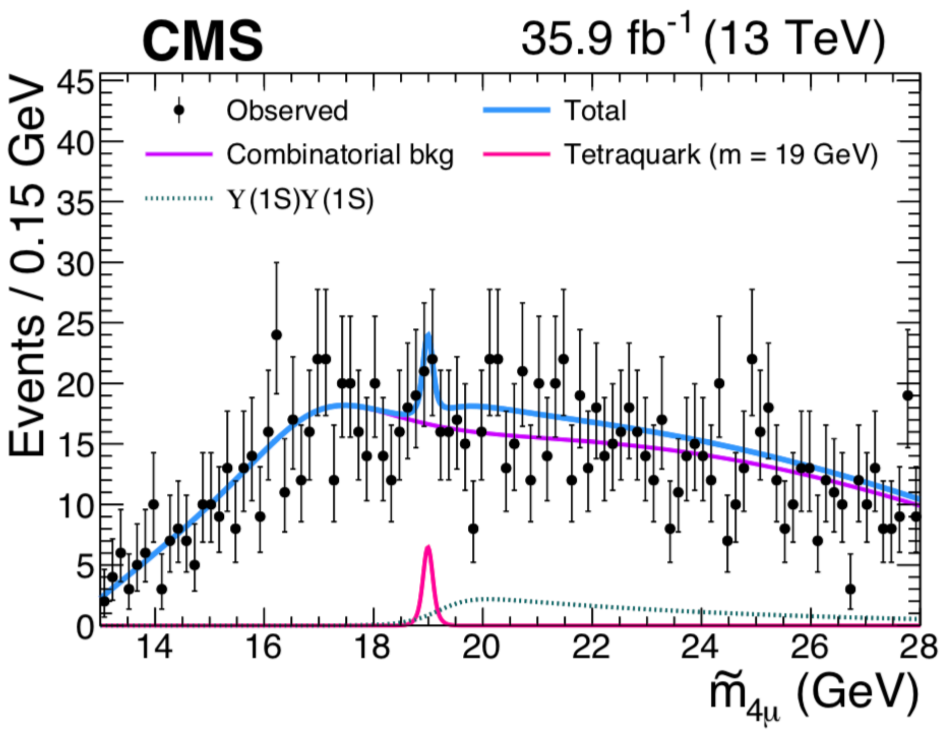
Upper limit at 90% (95%) C.L. within 8 – 32 (11 - 36) fb.

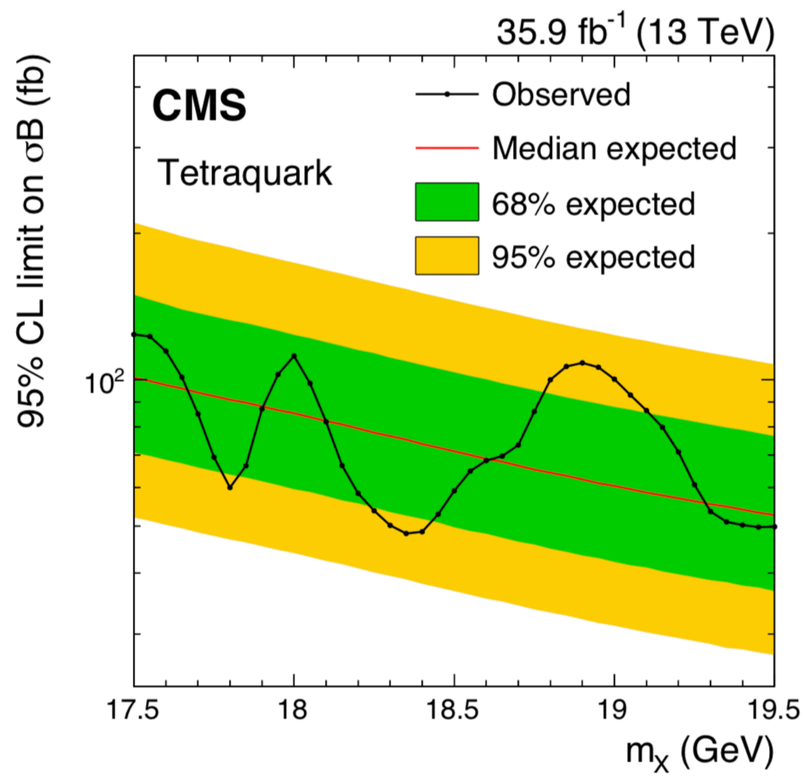
Search for $T_{b\bar{b}b\bar{b}}$ by CMS

- Two must have an invariant mass compatible with a Υ resonance
- ($8.5 < m_{2\mu} < 11.4$ GeV)
- Rapidities y < 2 and p_T less than 10 GeV/c.

PLB 808 (2020) 135578

$\sqrt{s}$ = 13 TeV, 35.9 fb^{-1} pp collisions data





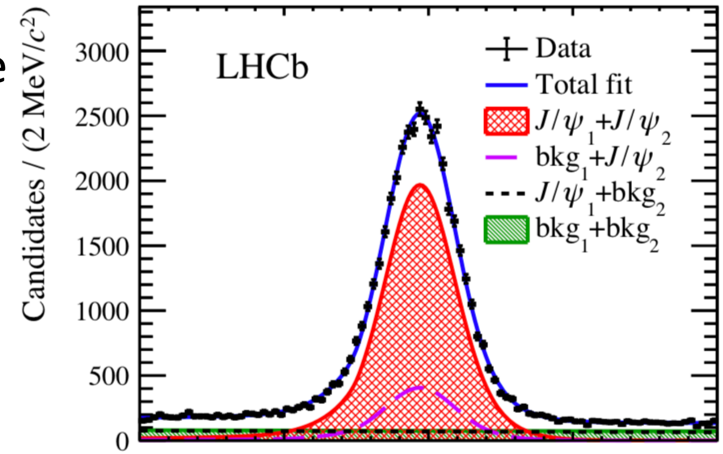
No excess of events compatible with a signal is observed.

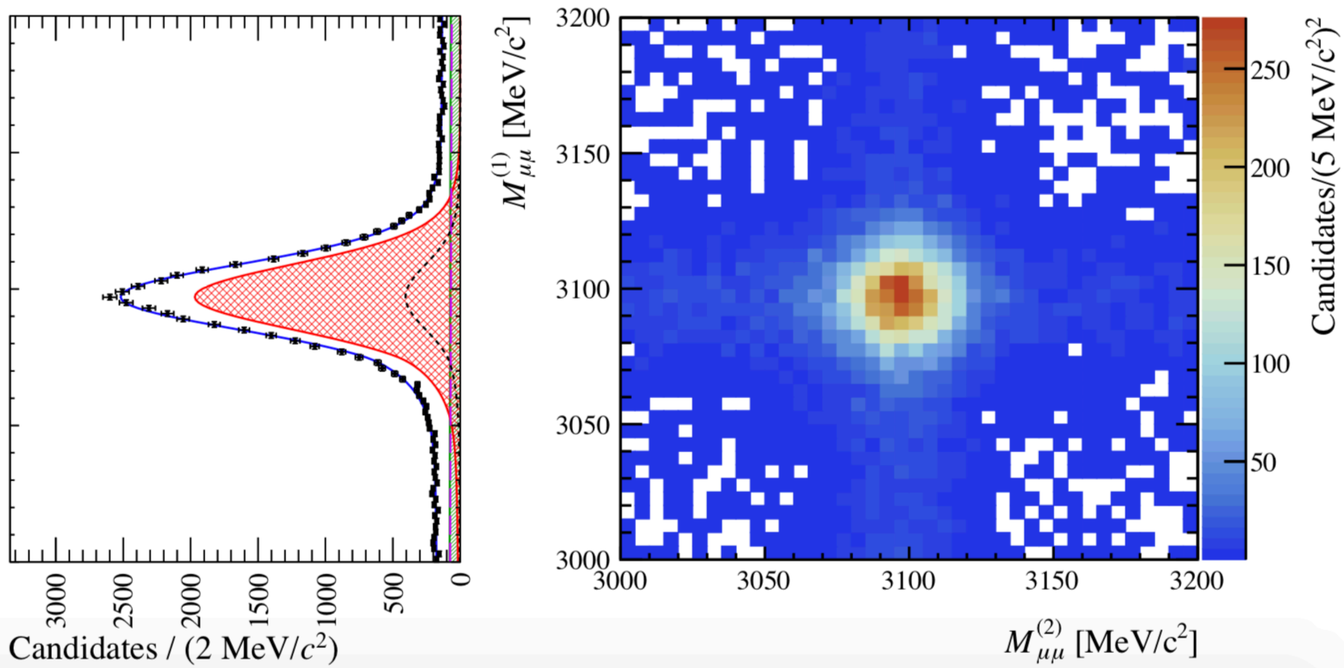
J/ψ pair from LHCb

Science Bulletin, 2020, 65(23)1983-1993

J/ψ pair signals are extracted from unbinned maximum-likelihood fit to the two-dimensional $(M_{\mu\mu}^{(1)}, M_{\mu\mu}^{(2)})$ mass distribution.

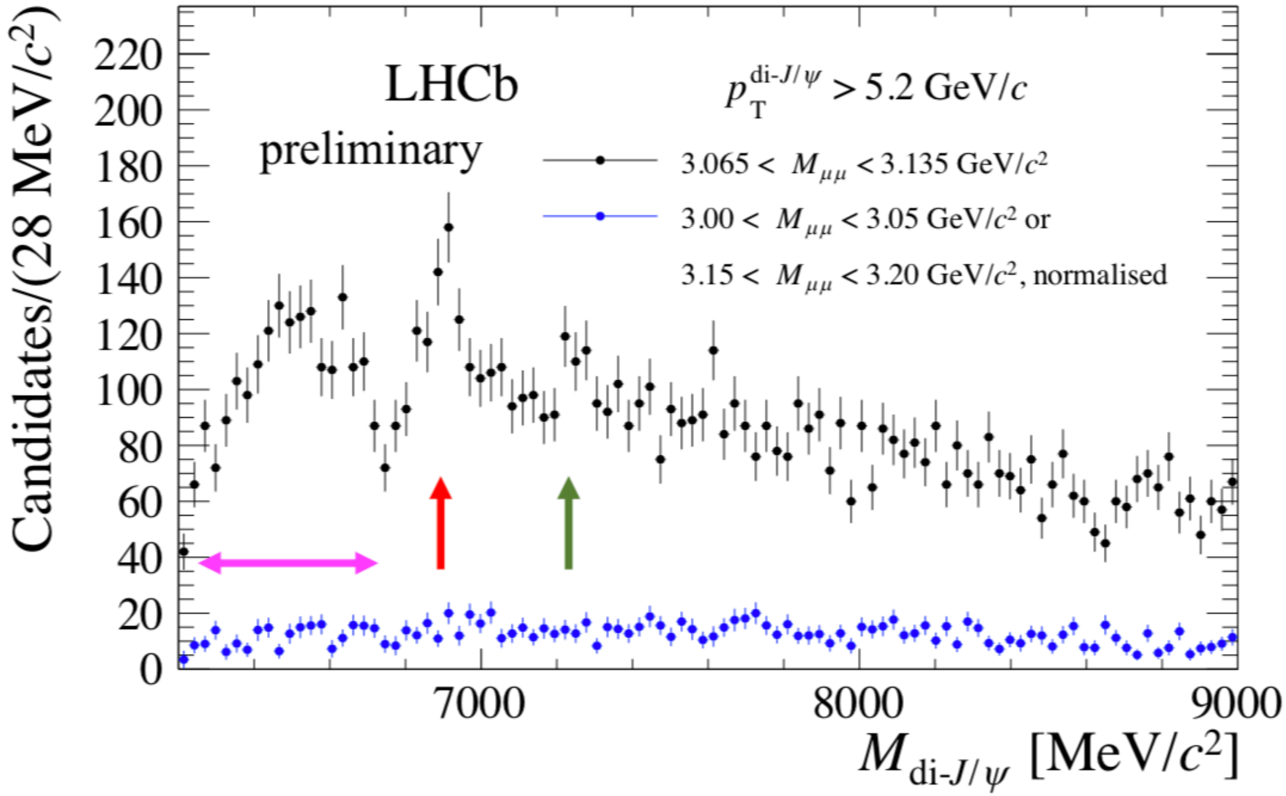
N(J/ψ pair) = $(33.57 \pm 0.23) \times 10^3$





J/ψ pair mass spectrum

Science Bulletin, 2020, 65(23)1983-1993

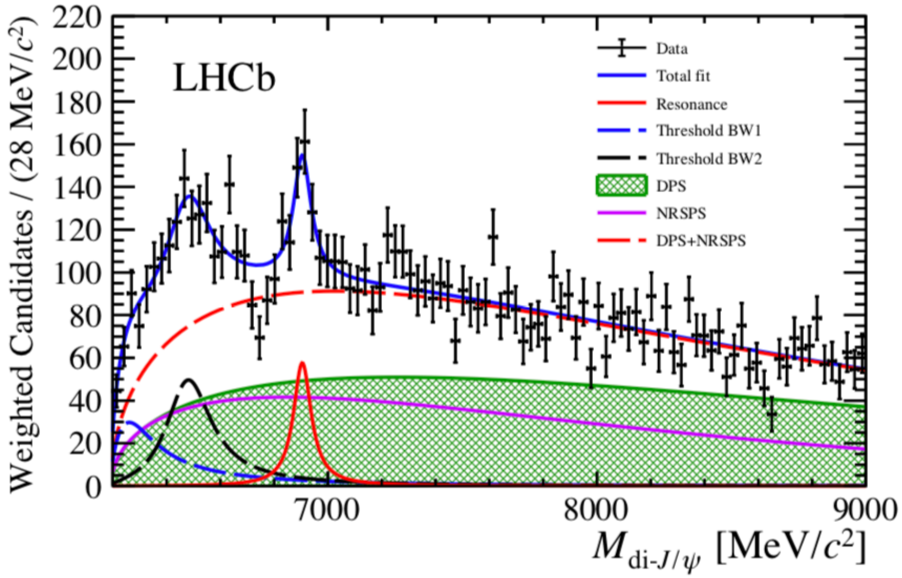


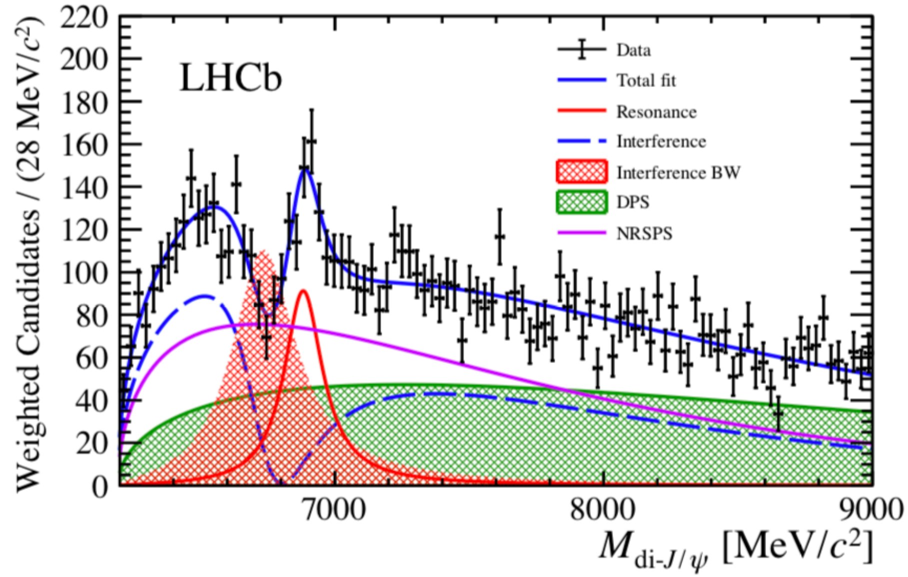
J/ψ pair mass spectrum shows

- **A broad structure** next to threshold ranging from 6.2 to 6.8 GeV/c^2
- **A narrow structure** at about 6.9 GeV/c^2
- **A Hint** for another structure around 7.2 GeV/c^2
- **No evidence for further structures above 7.2 GeV/c^2**

Fits to J/ψ pair mass spectrum

Science Bulletin, 2020, 65(23)1983-1993 Interference between resonant and non-resonant components





One $T_{c\bar{c}c\bar{c}}$ state for 6.9 GeV/c^2 peak + two $T_{c\bar{c}c\bar{c}}$ states for threshold structure

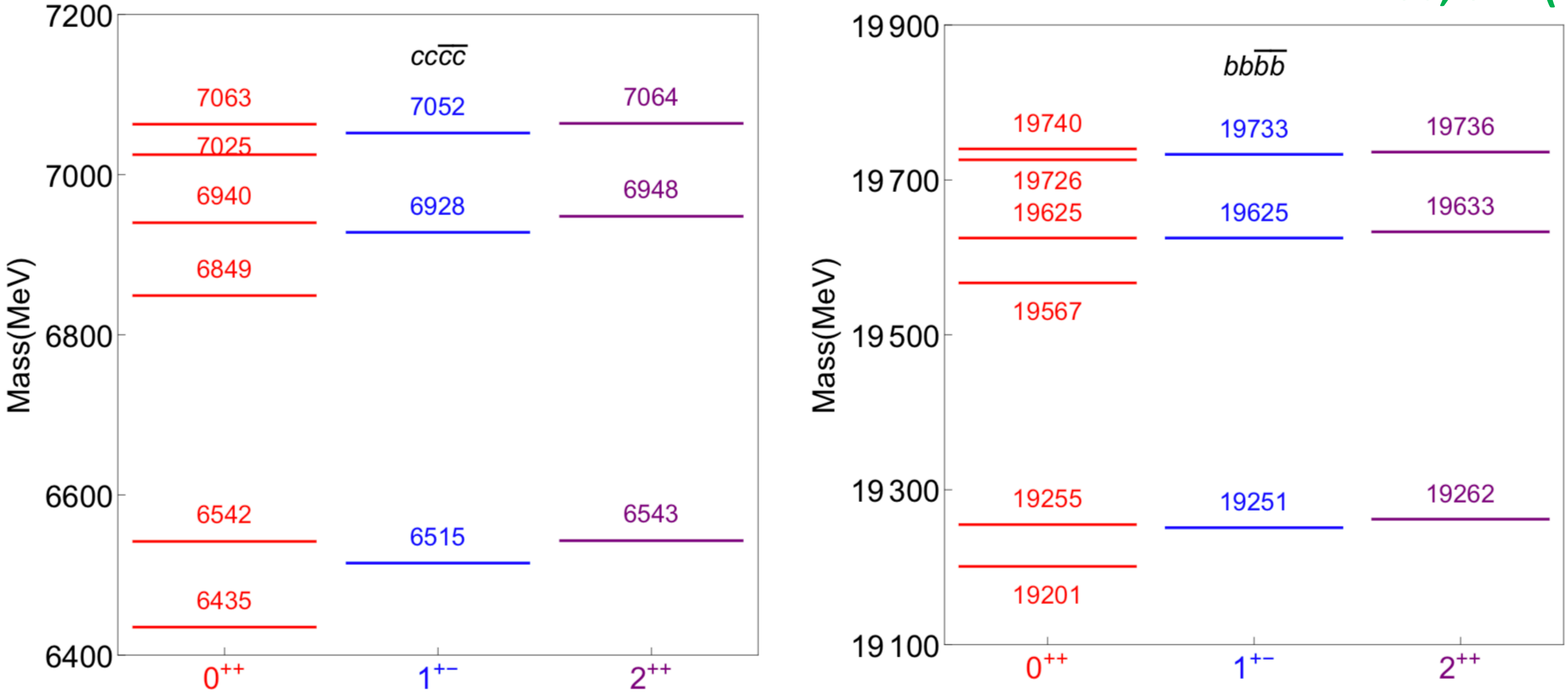
One $T_{c\bar{c}c\bar{c}}$ state for 6.9 GeV/c^2 peak + a lower-mass state interference with non-resonance

X(6900)	No-interference	Interference
Mass	6905 ± 11 ± 7	6886 ± 11 ± 11
Width	80 ± 19 ± 33	168 ± 33 ± 69
Signal yield	252 ± 63	784 ± 148
Significance	> 5σ	> 5σ

@CEPC

- **Confirm $T_{c\bar{c}c\bar{c}} \rightarrow$ J/ψJ/ψ by LHCb**
- **Explore more and more $T_{c\bar{c}c\bar{c}}$ and $T_{b\bar{b}b\bar{b}}$ states**

EPJC 80, 871 (2020)



System	J^P	$S-$wave	$P-$wave
$cc\bar{c}\bar{c}$	0^{++}	$\eta_c\eta_c$, $J/\psi J/\psi$, $\eta_c(2S)\eta_c$, $\psi(2S)J/\psi$, h_ch_c, $\chi_{c0}\chi_{c0}$, $\chi_{c1}\chi_{c1}$, $\chi_{c2}\chi_{c2}$	$\eta_c\chi_{c1}$, $J/\psi h_c$, $\eta_c(2S)\chi_{c1}$, $\psi(2S)h_c$
	1^{+-}	$\eta_c J/\psi$, $\eta_c(2S)J/\psi$, $\eta_c\psi(2S)$, $h_c\chi_{c0}$, $h_c\chi_{c1}$, $h_c\chi_{c2}$	$\eta_c h_c$, $J/\psi\chi_{c0}$, $J/\psi\chi_{c1}$, $J/\psi\chi_{c2}$, $\eta_c(2S)h_c$, $\psi(2S)\chi_{c0}$, $\psi(2S)\chi_{c1}$, $\psi(2S)\chi_{c2}$
	2^{++}	$J/\psi J/\psi$, $\psi(2S)J/\psi$, h_ch_c, $\chi_{c1}\chi_{c1}$, $\chi_{c2}\chi_{c2}$	$\eta_c\chi_{c1}$, $\eta_c\chi_{c2}$, $J/\psi h_c$, $\eta_c(2S)\chi_{c1}$, $\eta_c(2S)\chi_{c2}$, $\psi(2S)h_c$
$bb\bar{b}\bar{b}$	0^{++}	$\eta_b\eta_b$, $\Upsilon\Upsilon$, $\eta_b(2S)\eta_b$, $\Upsilon(2S)\Upsilon$, h_bh_b, $\chi_{b0}\chi_{b0}$, $\chi_{b1}\chi_{b1}$, $\chi_{b2}\chi_{b2}$	$\eta_b\chi_{b1}$, Υh_b, $\eta_b(2S)\chi_{b1}$, $\Upsilon(2S)h_b$
	1^{+-}	$\eta_b\Upsilon$, $\eta_b(2S)\Upsilon$, $\eta_b\Upsilon(2S)$, $h_b\chi_{b0}$, $h_b\chi_{b1}$, $h_b\chi_{b2}$	$\eta_b h_b$, $\Upsilon\chi_{b0}$, $\Upsilon\chi_{b1}$, $\Upsilon\chi_{b2}$, $\eta_b(2S)h_b$, $\Upsilon(2S)\chi_{b0}$, $\Upsilon(2S)\chi_{b1}$, $\Upsilon(2S)\chi_{b2}$
	2^{++}	$\Upsilon\Upsilon$, $\Upsilon(2S)\Upsilon$, h_bh_b, $\chi_{b1}\chi_{b1}$, $\chi_{b2}\chi_{b2}$	$\eta_b\chi_{b1}$, $\eta_b\chi_{b2}$, Υh_b, $\eta_b(2S)\chi_{b1}$, $\eta_b(2S)\chi_{b2}$, $\Upsilon(2S)h_b$

Summary

- Advantages @Tera-Z CEPC: cleaner LEP environment, larger acceptance wrt LHCb; larger boost, no phase-space limitations wrt Belle.
- Measure the absolute Brs of X(3872).
- Confirm the recent exotic states results from LHCb, and search for Ω_{cc}^{+}(scc), Ξ_{bc}(bcq), Ξ_{bb}(bbq), $T_{c\bar{c}c\bar{c}}$, $T_{b\bar{b}b\bar{b}}$, etc at CEPC.
- Dedicate the exotica productions from B_s, Ξ_b, and Ω_b decays.

Thank you !

Backup slides

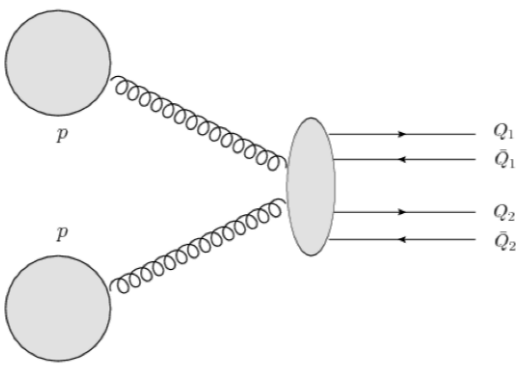
Stable doubly heavy tetraquark

In Ref. [164], Eichten and Quigg calculated the masses of the $QQ\bar{q}\bar{q}$ ($Q = c, b$, $q = u, d, s$) tetraquark states based on mass relations obtained from the heavy quark symmetry and finite-mass corrections. According to their results, the $I(J^P) = 0(1^+)$ $cc\bar{u}\bar{d}$ state is 102 MeV above the D^+D^{*0} threshold, while the $bb\bar{u}\bar{d}$ state is 121 MeV below the $B^-\bar{B}^{*0}$ threshold. The finding is consistent with that by Karliner and Rosner [166]. Besides, this calculation indicated a stable $bb\bar{n}\bar{s}$ bound state with $I(J^P) = 0(0^+)$ but no stable $bc\bar{u}\bar{d}$.

State	J^P	j_ℓ	$m(Q_iQ_jq_m)$ (c.g.)	HQS relation	$m(Q_iQ_j\bar{q}_k\bar{q}_l)$	Decay channel	$\mathcal{Q}$ (MeV)
$\{cc\}[\bar{u}\,\bar{d}]$	1^+	0	3663[b]	$m(\{cc\}u) + 315$	3978	D^+D^{*0} 3876	102
$\{cc\}[\bar{q}_k\bar{s}]$	1^+	0	3764[c]	$m(\{cc\}s) + 392$	4156	$D^+D_s^{*-}$ 3977	179
$\{cc\}\{\bar{q}_k\bar{q}_l\}$	$0^+, 1^+, 2^+$	1	3663	$m(\{cc\}u) + 526$	4146,4167,4210	D^+D^0, D^+D^{*0} 3734,3876	412,292,476
$[bc][\bar{u}\,\bar{d}]$	0^+	0	6914	$m([bc]u) + 315$	7229	B^-D^+/B^0D^0 7146	83
$[bc][\bar{q}_k\bar{s}]$	0^+	0	7010[d]	$m([bc]s) + 392$	7406	B_sD 7236	170
$[bc]\{\bar{q}_k\bar{q}_l\}$	1^+	1	6914	$m([bc]u) + 526$	7439	B^*D/BD^* 7190/7290	249
$\{bc\}[\bar{u}\,\bar{d}]$	1^+	0	6957	$m(\{bc\}u) + 315$	7272	B^*D/BD^* 7190/7290	82
$\{bc\}[\bar{q}_k\bar{s}]$	1^+	0	7053[d]	$m(\{bc\}s) + 392$	7445	DB_s^* 7282	163
$\{bc\}\{\bar{q}_k\bar{q}_l\}$	$0^+, 1^+, 2^+$	1	6957	$m(\{bc\}u) + 526$	7461,7472,7493	BD/B^*D 7146/7190	317,282,349
$\{bb\}[\bar{u}\,\bar{d}]$	1^+	0	10 176	$m(\{bb\}u) + 306$	10 482	$B^-\bar{B}^{*0}$ 10 603	$\boxed{-121}$
$\{bb\}[\bar{q}_k\bar{s}]$	1^+	0	10 252[c]	$m(\{bb\}s) + 391$	10 643	$\bar{B}\bar{B}_s^*/\bar{B}_s\bar{B}^*$ 10 695/10 691	$\boxed{-48}$
$\{bb\}\{\bar{q}_k\bar{q}_l\}$	$0^+, 1^+, 2^+$	1	10 176	$m(\{bb\}u) + 512$	10 674,10 681,10 695	B^-B^0, B^-B^{*0} 10 559,10 603	115,78,136

Prompt J/ψ pair production

Single parton scattering (SPS)



Double parton scatterings (DPS)